Master Thesis, Department of Geosciences

Late Cenozoic evolution of the northern North Sea and North Sea Fan: A seismic sequence stratigraphic analysis

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Abstract

The Late Cenozoic outbuilding in the northern North Sea and southeastern Norwegian Sea demonstrates strong relationship between uplift, erosion, subsidence, variations in relative sea level, basin infill, glacial dynamics and climate.

The study is made to get better understanding of the Plio-Pleistocene outbuilding in reference to glacial-interglacial or/and stadial-interstadial cyclicity, variation in accommodation space, as function of basin subsidence, glacioeustacy, and glacial dynamics and sedimentation. A total of 31 sequences, along with the SS-A to SS-D sequences in the Norwegian Channel, were observed, and are interpreted mainly to represent glacial-interglacial cycles. In terms of seismic stratigraphical geometry and architecture three distinct depositional regimes have been observed in present study and have been named as megasequence I, megasequence II and NSF megasequence.

Megasequence I contains steep prograding clinothems. The prograding clinothems are built by glacially derived sediments sourced from the uplifted southwestern mainland Norway. Megasequence II was formed in the Norwegian Channel by fast flowing ice streams gouging the sediment around the coast of southern Norway. The flat successions, overlying a near-margin 1.1 Ma erosion surface, consist of till, glacial marine and marine sediments. The megasequence NSF (North Sea Fan) consists of prograding wedges that developed by the fast flowing ice streams in the Norwegian Channel. The continued aggradation in the channel subsequently gave rise to progradation of the North Sea Fan. An effort was made to correlate sequences that have been found in the Norwegian Channel with those that have been identified in the North Sea Fan.

The environment of deposition for the sequences has been determined using seismic facies. Furthermore, four main seismic facies has been has been identified that equate glacigenic debris flows, glaciomarine sediments, slide debrites and hemipelagic/contourite sediments.

The recorded 31 glacigenic sequences have been correlated with glacial records form the mid-Norwegian continental shelf, from deep-sea sediments and from Iceland. The correlations confirm that the number of glaciations that impacted the depositional history of the Norwegian shelf well may be in the order of 30.

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1. Introduction

During late Cenozoic a prominent shift in sedimentation occurred in the North Sea and Norwegian Sea along the Norwegian mainland. From clay-dominated sedimentation during Eocene to early Pliocene, large prograding clastic wedges accumulated in the northern North Sea and the mid-Norwegian shelf during late Pliocene and Pleistocene. This large-scale outbuilding of the shelf was the result of diverse controlling factors, such as uplift of mainland Norway and global cooling. Increased erosion and sediment supply to the shelf, primarily by glacial ice, gave rise to deposition of huge amounts of glacially derived sediments.

The glacial history of the southern Norwegian shelf and its hinterland can be attained from sedimentary successions on the shelf, at the shelf edge, on the continental slope and in the deep-marine basin, deposits of till, glacigenic debris flows, slide deposits, hemipelagic sediments and ice-rafted debris (IRD), besides sequence development and depositional architecture (e.g. King et al., 1996; Dowdeswell et al., 1995; Hjelstuen et al., 2005; Nygård et al., 2005; Sejrup et al., 2003, 2004).

The North Sea Fan represents a major depocenter of Pleistocene glaciomarine sedimentation in the northern North Sea and adjacent part of the southeastern Norwegian Sea. The Pleistocene glacigenic succession contains thick shelf prograding clinothems of glacigenic debis flows and slide debrites, separated by clinoform surfaces, downlapping onto a regional downlap surface (RDS). The sliding activity eroded the slope sequences repeatedly throughout the deposition of the glacial column. The prograding clinothems are upwards bounded by an upper regional unconformity (URU), a polycyclic surface formed by glacial erosion. On the inner part of the shelf, URU separates overlying aggradational till units from the seaward dipping strata of the shelf prograding wedges below the unconformity. In westward direction beyond the shelf break, the URU turns to be a conformable boundary. The aggradational till sequences on the shelf reflect a large number of depositional and erosional episodes, thus most tills have limited lateral distribution (Sejrup et al., 1996; Lee et al., 2010). The position of the study area is shown in Figure 1.1.

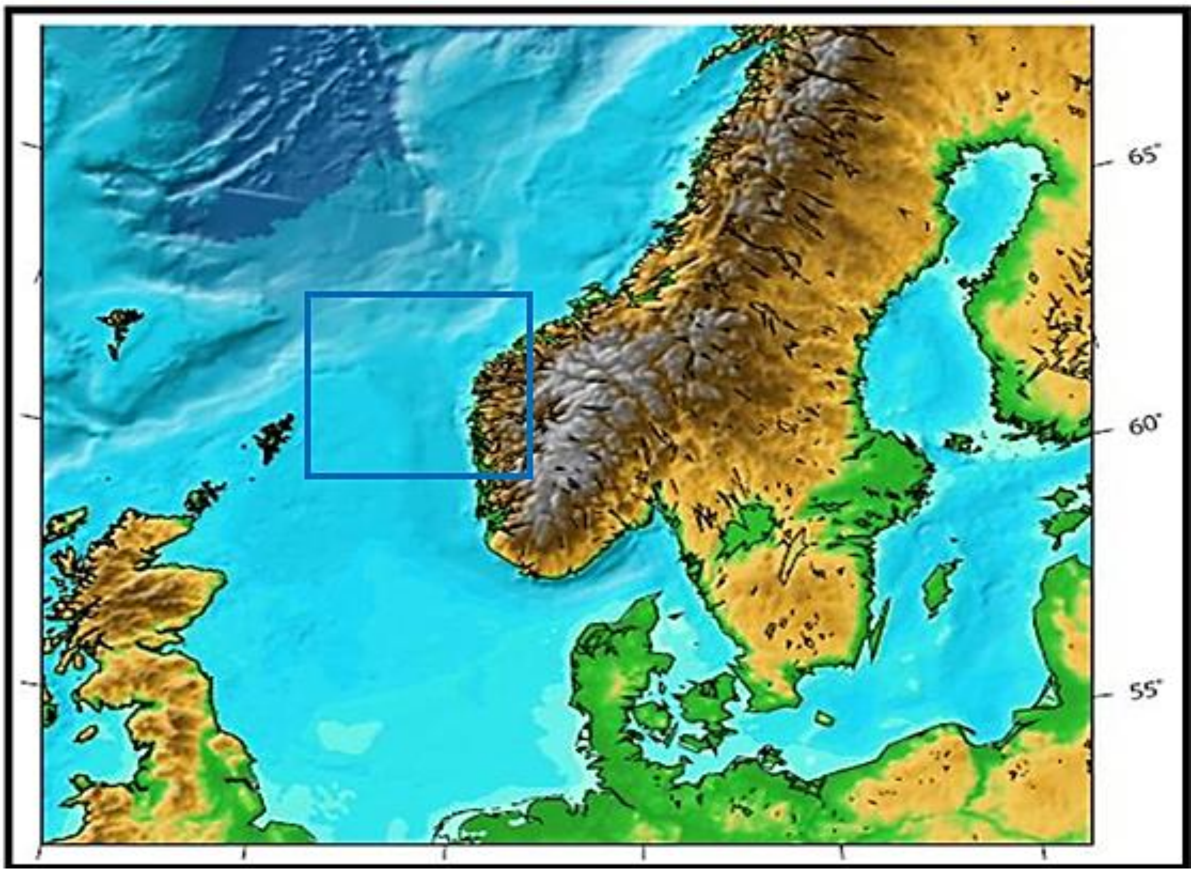

Fig. 1.1: Regional setting and location of the study area.

The objective of the present master thesis is to study the Late Cenozoic shelf outbuilding of the North Sea Fan and adjacent areas, including the northern part of the Norwegian Channel, which is supposed to have been a major pathway for glacigenic sediment transport to the North Sea Fan (King et al., 1996; Nygård et al., 2005). The main scope of the work is to define, map and number seismic sequences that, from a working hypothesis, can be interpreted to be the results of glacial cyclicity, either complete glacial-interglacial cycles or/and stadial/interstadial cycles, and to correlate these with glacial cyclicity with the order of 20-30 glaciations, or more, interpreted from deep-sea sediments, from Iceland till stratigraphy (Geirsdóttir et al., 2007) and from seismic stratigraphy of the mid-Norwegian shelf (Rise et al., 2005, 2010; Hafeez, 2011; Talat, 2012) . In addition, the glacigenic depositional development of the study ara will be related to changes and variation in sediment supply, accommodation and glacial dynamics.

2. Geological Setting

The present study area is located in the northern North Sea and adjacent part of the Møre Basin. The depositional setting for the late Pliocene to Pleistocene glacial and glaciomarine succession in the area is inherited from a long geological history that affected the basinal area as well as the sediment source area. Tectonic activity that developed the present structural makeup can be traced back to Permian and Carboniferous times (Bukovics and Ziegler, 1985). Three main rifting phases occurred during Carboniferous to Permian, late Mid-Jurassic to Early Cretaceous and late Cretaceous to Early Eocene times (Brekke, 2000). Although extensional tectonics in the North Sea and in adjacent regions of the North Sea begun as early as the late Carboniferous, continental separation between Greenland and Norway was initiated first after the late Paleocene (Doré et al., 1999).

The Early Permian-Triassic rifting in the North Sea area is poorly constrained. During Jurassic–early Cretaceous, the North Sea region suffered significant rifting. This rifting ended in the earliest Cretaceous and shifted to the Møre, Vøring and Faroe–Shetland basins. After this period, the North Sea Basin thermally subsided and was filled with sediments sourced from the surrounding landmasses, interrupted periodically by basin inversion (Ziegler, 1990).

Crustal extension remained during Late Paleozoic in the continental crust segment between Norway and Greenland, and continued in several rifting episodes during the Mesozoic. Crustal extension affected outer parts of the Møre and Vøring basins during Late Cretaceous-Paleocene, which later on shifted towards the central part of the basins with the passage of time (Doré et al., 1999; Brekke et al., 2001).

2.1 Cenozoic

The crust between Norway and Greenland was ruptured and weakened by the late Paleozoic and Mesozoic rifting events and finally broke up during the Paleogene (Svensen et al., 2004; Henriksen et al., 2005). The final breakup took place in Paleocene-Eocene (~ 55-54 Ma), with huge amounts of lava erupting during the breakup. During the magmatic activity sills intruded into the Cretaceous successions throughout the NE Atlantic margins (Svensen et al., 2004; Henriksen et al., 2005; Planke et al., 2005; Faleide et al., 2008) (Fig. 2.1).

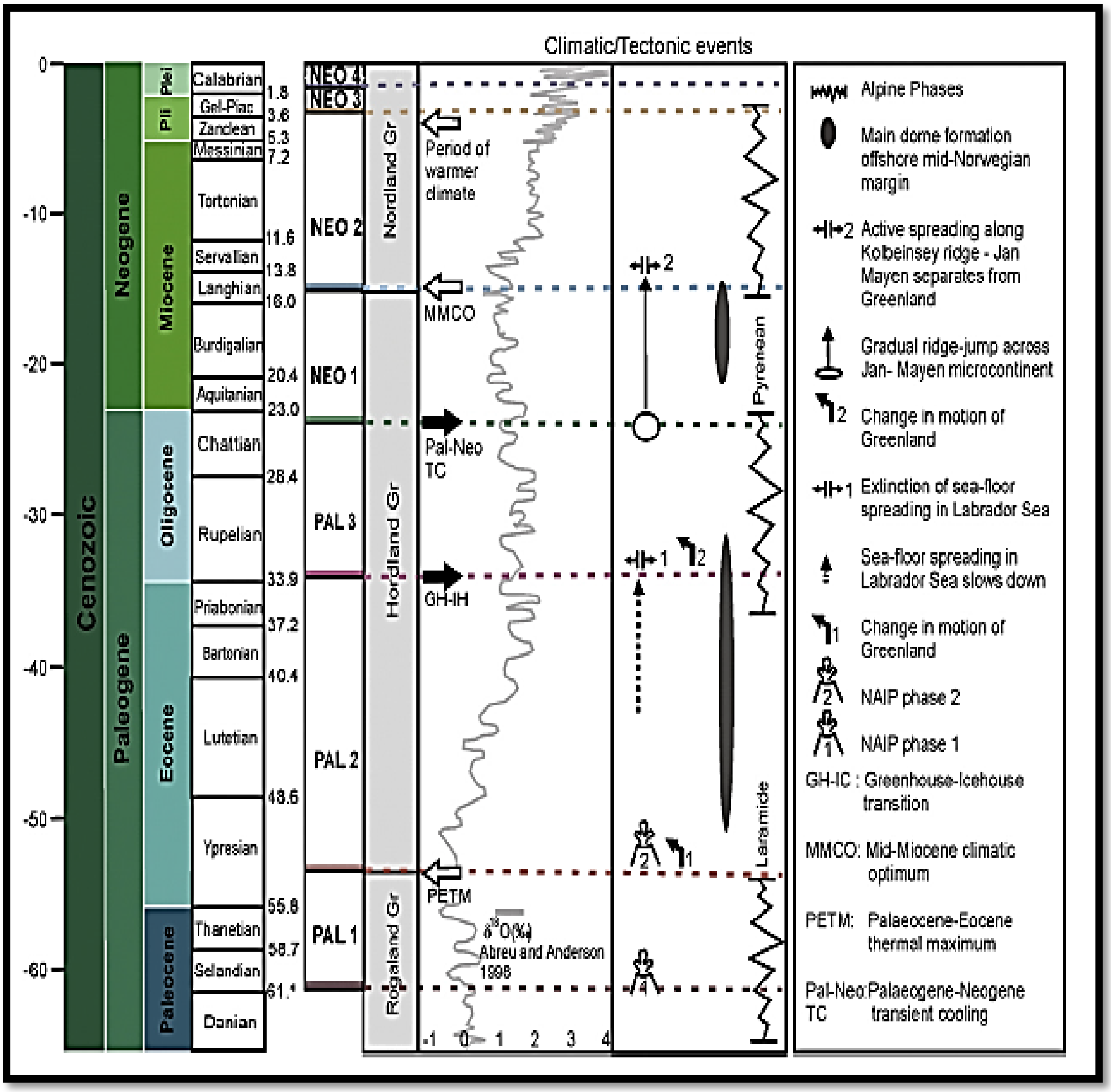

Fig. 2.1:.Main tectonic and climatic events during the Cenozoic in the northern North Sea area (after Anell et al., 2010)

The Miocene succession in the northern North Sea – Møre Basin area shows the record of deep water sedimentation that indicates expansion of contourite sediment drifts in the open Norwegian-Greenland Sea (Eiken and Hinz, 1993; Stoker et al., 2005, Faleide et al., 2008).

The NW European margin went through compression and structural inversion phases in Early Neogene time (Fig. 2.1). The compressional phase reactivated older faults and caused inversion structures like the Ormen Lange Dome in the Møre Basin and several similar structures in the Vøring Basin (Blystad et al., 1995; Løseth and Henriksen, 2005). During the Late Neogene the Norwegian mainland was uplifted (Smelror et al., 2007) (Fig. 2.1). Cenozoic subsidence of the NE Atlantic margins is thought to be related to the uplift and erosion of the continental margins and is also episodic in character (Stocker et al., 2005). Erosion, sediment flux and rate of sedimentation was also controlled by climatic changes, particularly by the change from warm to cold climate during Pliocene time (Anell et al., 2010) (Fig. 2.1).

2.1.1 Uplift mechanisms

Different causes of Cenozoic uplift have been suggested (Faleide et al., 2002; Osmundsen and Redfield, 2011). These includes, among others, arrival of the Iceland plume and resulting lateral spreading (Smelror et al. 2007), isostatic rebound resulted by the removal of ice sheets and intra-plate stress caused by rearrangement of plate or mantle dynamics (Stoker et al., 2005), and super-extension of the continental crust (Osmundsen & Redfield, 2011). During the Late Neogene Southern Norway was uplifted approximately 1000 – 3000 m (Riis, 1996; Smelror et al., 2007; Lidmar-Bergström et al., 2013).

2.1.2 Depositional environment

During Paleocene, both the Møre and Vøring basins were filled with thick sediments sourced from the eastern and western elevated margins and marginal highs. The Eocene depocenter located in the central and northern North Sea shows the outbuilding into the basin from the uplifted Shetland Platform (Faleide et al., 2002).

During the Early Miocene the northern North Sea was a shallow marine basin as indicated by many incised valleys and channels and coarsening upward strata in the basin (Gregersen, 1998; Rundberg and Smalley, 1989). This may be due to uplift of the northern North Sea and South Norway. Percentage of sand increases in Early to Mid-Miocene sediments compared to Oligocene sediments that also indicate sea level fall during this period, or tectonic uplift. Through Neogene times, the depocenter and sediment thickness in the North Sea area have changed due to changing position of area of maximum subsidence and accommodation and to variation in clastic input (Anell et al., 2010' see figure 2.2).

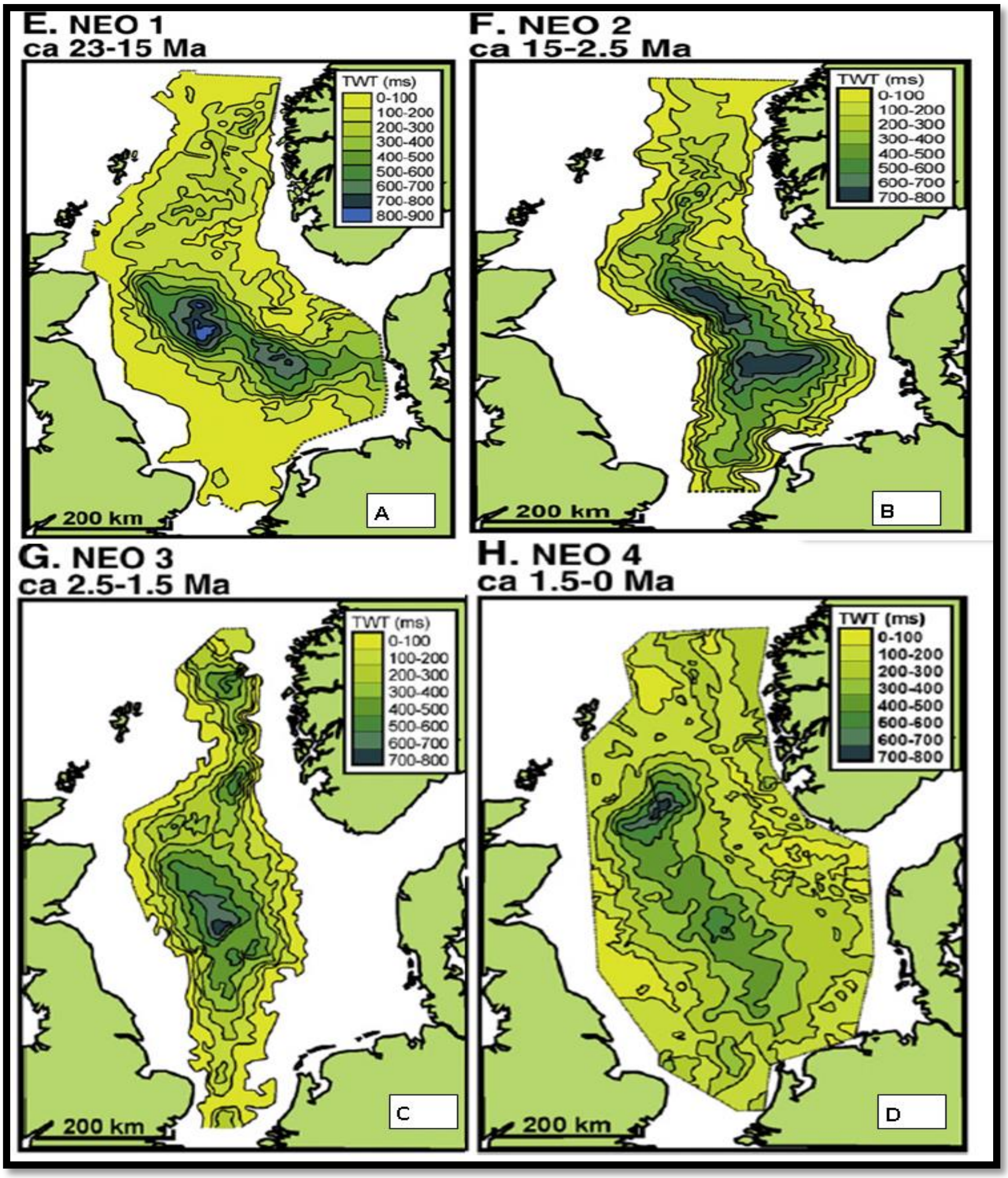

Fig.2.2: Time thickness maps from Miocene to present. A) Time thickness map of Early to Mid-Miocene, B) Mid-Miocene to Early Pliocene, 15–2.5 Ma, C) Pliocene- Pleistocene 2.5-1.5, D) Pleistocene 1.5 Ma to present (modified from Anell et al., 2010)

Continued uplift of Scandinavia resulted in the progradation of late Miocene deposits in westward direction. Late Miocene progradational wedges downlap onto the mid-Miocene unconformity (Faleide et al., 2002; Gregersen & Johannessen, 2007). Deep water starved conditions existed in the Danish and Møre basins during late Miocene (Faleide et al., 2002). During Late Miocene, the Utsira Formation was deposited in northern North Sea under restricted environmental conditions (Anell et al., 2010). During Neogene, the depocenter was located south of 60° (Faleide et al. 2002) (Fig. 2.2).

During the earliest Pliocene sea level rise and transgression too took place in the northern North Sea area. This event generally marked the period with lowest rate of sedimentation; most of the sediments of this time interval were eroded during the subsequent global sea level fall about 4.1-2.9 Ma ago. This fall in sea level caused regional regression and progradation of clastic shelf sediments into deep water settings along the Norwegian continental shelf (Eidvin et al., 2000). Many incised valleys were also formed during this time period (Faleide et al., 2002, Anell et al., 2010).

Sediment outbuilding in Plio-Pleistocene 2.5-1.5 Ma generally represents the progradational wedges above the regional downlap surface (RDS); the RDS generally represents a maximum flooding surface in the northern and central North Sea. The rate of accumulation in these deposits is about ten percent higher than during earlier Miocene sedimentation (Anell et al., 2010). The seismic sequence CSS8 which is equal to the NEO-3 of Anell et al., (2010), represents this time period and the major depocenter of this sequence is located mainly in the northernmost North Sea. The sediments comprised mainly of glacially derived clastic debris. The dominant transport direction was located towards the west and north-west (Faleide et al., 2002) (Fig. 2.2). This time period, characterized by dominantly glacial and glaciomarine sedimentation, is related to the marked expansion of glaciations on the northern hemisphere (Eidvin et al., 2000).

An angular unconformity was formed by glacial erosion in the study area during the early stages of glaciation, when ice sheets approached the western coast of Norway. The Fedje glaciation during 1.1 Ma is thought to be responsible for this unconformity. Less prograding to aggrading flat lying Pleistocene beds generally overlies the unconformity (Sejrup et al., 1995).

A sharp change in depositional geometry can be observed in the deposits belonging to this period. This is due to fact that the Fedje ice sheet did not extend to the shelf edge. After this period many cycles of shelf edge glaciations occurred. The largest depocenter for these deposits is believed to have been located in the North Sea Fan area (Sejrup et al., 1995, 2005). The lower boundary Pleistocene (1.5-0 Ma) is a composite unconformity between the 1.5 Ma (Base Pleistocene) and 1.1 Ma glacial formed unconformity. Accumulation rates were higher during Pleistocene and the principle outbuilding direction was from SSE to NNW

(Anell et al., 2010). The Norwegian Channel was the main drainage system of fast flowing ice streams during the Pleistocene. An aggradational succession of till and glacial to marine sediments was deposited in the Norwegian Channel (Sejrup et al., 2005).

Glacial processes resulted in high sediment input from elevated areas and deposition in topographical lows during Late Pliocene and Pleistocene (Henriksen et al., 2005). During glacial and interglacial intervals isostatic uplift of land and subsequent erosion was prominent. The bottom of glacial ice sheets got warm by overloading of thick ice masses, the bottom ice melted at its pressure-melting point, and the wet glacier ice sheet moved. Bedrock and previously deposited sediments were eroded as the ice sheet moved (Bryn et al., 2005).

This is the main processes through which glacial ice may produce large quantities of sediments. In the present study area, the North Sea Fan shows to be the main depocenter for such glacially formed deposits. High sediment supply from the calving fronts of glacier ice sheets created mass instability and creation of large slides in the North Sea Fan area, such as the Møre and Tampen slides. These slides are interpreted to be related to three extensive glaciation periods: the Elsterian, Saalian, and Weichelian (Rise et al., 2005).

For submarine slides to be formed there should be some process or processes that cause the slope instability. According to Sultan et al. (2004), such processes may comprise 1) high sedimentation rate that build-up excess pore pressure, 2) flexure by static load, i.e. by load of ice sheet, 3) fast loading by a dynamic weight such as an upslope landslide, and 4) Seismic loading due to earthquakes, low tides and storm-wave loading. Earthquake is considered as the main triggering mechanism of subsea slides at the Norwegian continental margin (Laberg & Vorren, 2002).

2.2 Stratigraphy

In Paleogene the Rogland Group was deposited and is composed of the shallow marine shale, marginal marine sandstone and volcanic deposits that are of Eocene age. The Neogene contains the Hordaland and Nordland groups (Eidvin et al., 2000) (Fig. 2.3).

The lower Neogene succession represents the deep water sedimentation, as indicated by the expansion of the contourite sediment drift above the sub marine unconformity. The upper Neogene represent a period of regional change that shows a major seaward shift (progradation) of the continental margin that could be due to subsidence. The building of the shelf slope shows increase in sediment supply due to uplift and erosion (Stoker et al., 2005).

The Nordland Group (Dalland et al., 1988) of Early Miocene-Recent age is of prime importance in present study and its main aspects as background for the present study is presented below (Fig. 2.3).

2.2.1 Utsira Formation

The Utsira Formation is of Middle-Late Miocene age and was deposited in the northern North Sea area, mainly within the Norwegian sector, between the Jæren High and the Tampen Spur. This formation shows a complex depositional architecture which varies with latitude. Around 58° N in the southern Viking Graben, the formation forms a giant mounded sand system with scattered intervals of mudstone. This sand mound is pinching mainly out both eastward and westward (Rundberg & Eidvin, 2005).

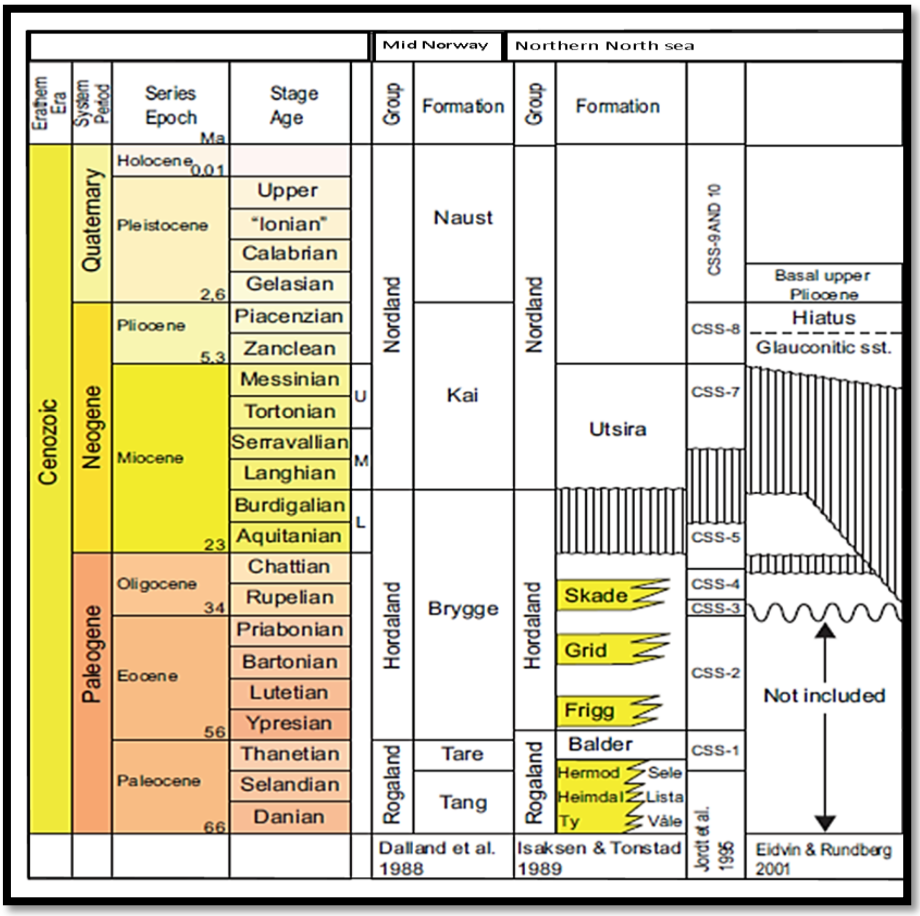

Fig. 2.3: Generalized lithostratigraphy of mid-Norway and northern North Sea based upon the new time scale (Jordt et al., 1995; Løseth et al., 2013).

Around 59° N the Utsira Formation is characterized by blocky sandstone in lower part, while the upper part shows a clear upward coarsening trend in well logs. In the northern Viking Graben (60°- 61° N), the Utsira Formation, represented by a mounded sandstone body, mainly consists of blocky sandstone with subordinate mudstone intervals. In its northward extension to Tampen area the Utsira Formation is displayed by a think unit of glauconitic sand). The Utsira Formation is considered time equivalent to the Molo Formation (Isaksen et al., 1989; Eidvin et al., 2001, 2007)

2.2.2 Naust Formation

The Naust Formation is composed of sand, silt, clays and occasionally coarse grained clastic sediments. The formation represents Pliocene to Pleistocene strata on the Norwegian continental shelf. The Naust Formation is distributed all over the Mid- Norwegian continental shelf (Dalland et al., 1988; Ottesen et al. 2009). The formation is comprised of a westward prograding thick succession of Plio-Pleistocene strata on the shelf and consists of several incoherent seismic units of till, glaciogenic debris and slide deposits. The glacial seismic units of the Naust Formation are interstratified with interglacial deposits (Rise et al., 2005, 2010).

The Naust Formation downlaps onto the Kai Formation and is in the eastward direction bounded below by the Molo Formation (Ottesen et al., 2009). Several ages have been assigned to the base of the Naust Formation, but the age that has been most widely used is 2.7 to 2.8 Ma. This age has been assigned on the basis of the biostratigraphic data correlated with the deep sea drilling cores (Edvin et al., 2000).

2.3 Late Cenozoic development of North Sea Fan

The North Sea Fan and the Norwegian Channel are two most important features that influenced the sedimentation in the study area during Pliocene – Pleistocene time.

2.3.1 North Sea Fan (NSF)

The North Sea Fan is located at the northern limit of the North Sea and the southern part of the Norwegian Sea. The Storegga slide marks the northeastern boundary of the fan and the Faroe-Shetland ridge marks south-western limit of the fan (Dahlgren et al., 2005) (Fig. 2.4).

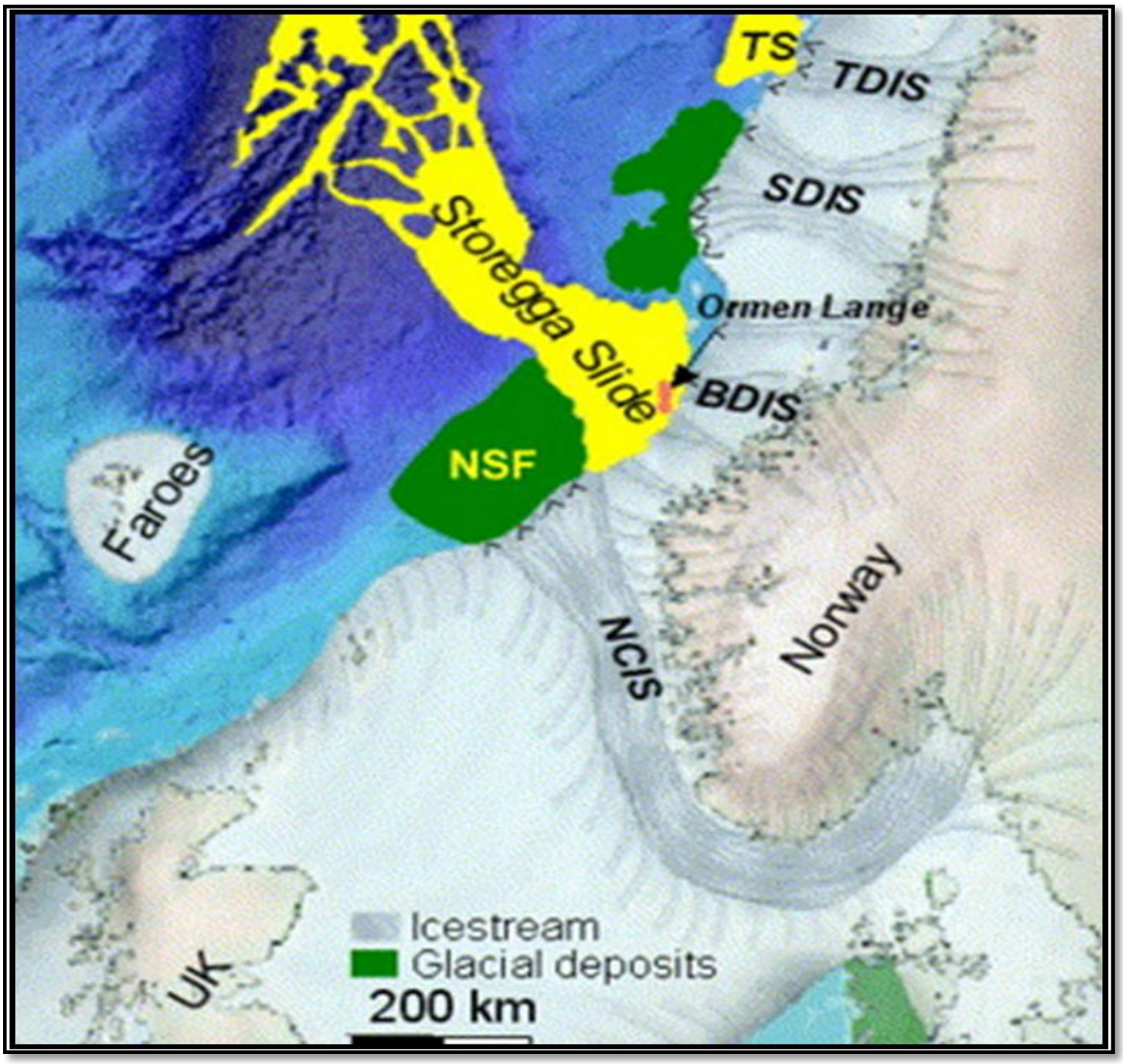

Fig. 2.4:.Location of the North Sea Fan (NSF) and the Norwegian Channel with its ice streams (NCIS) (after Solheim et al. 2005)

The evolution of the Plio-Pleistocene North Sea Fan is mainly controlled by the repeated introduction of new glacigenic material by the NCIS (Norwegian channel ice stream) drained through the Norwegian Channel during peak glaciation periods (King et al., 1996, 1998; Nygård et al., 2005; Lee et al., 2012).

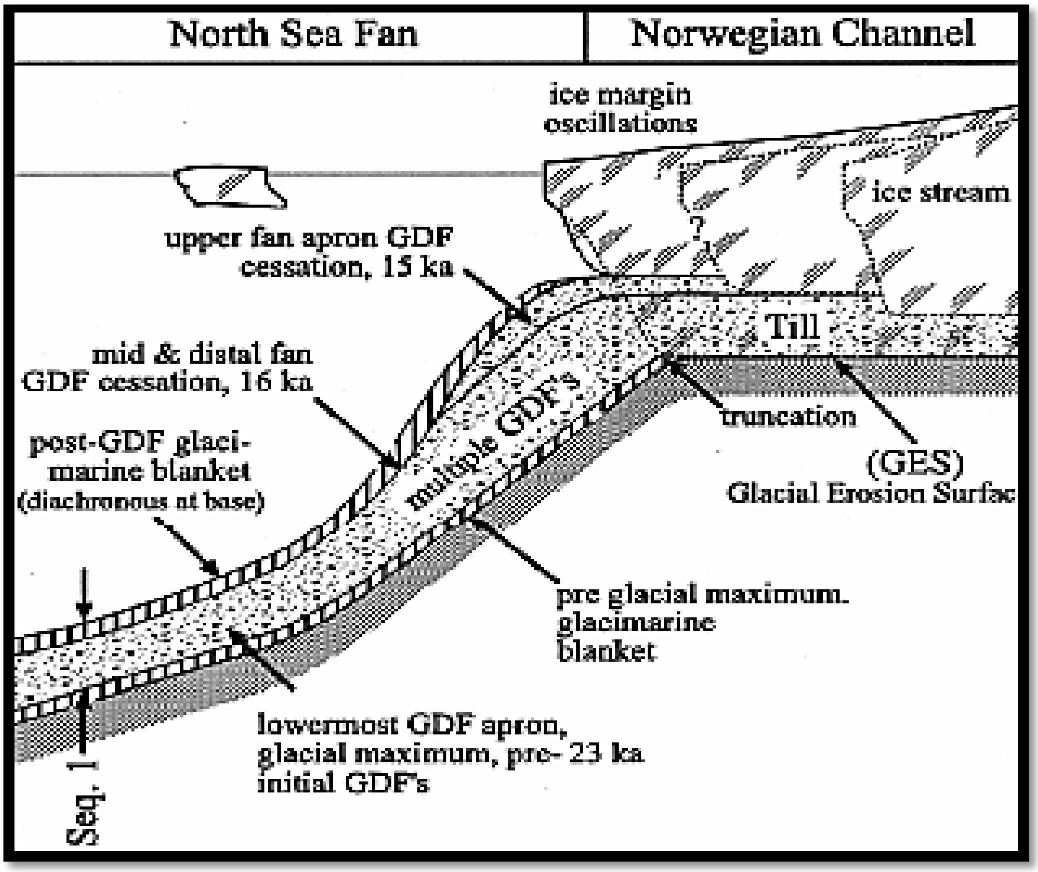

Fig. 2.5: Schematic diagram showing development of the uppermost fan sequence. In interstadial marine environment glaciomarine sediments deposited and GDFs (Glacigenic debris flow) occur during ice maximum (King et al., 1998).

Plio-Pleistocene succession of the North Sea fan is up to 1800 m think in upslope side. This succession is comprised of multiple glacigenic debris flows (GDFs), and intervening large slide debrites and marine sediments (King et al., 1996).

Glacigenic debris flow deposits in the fan are elongate bodies of reworked and re-deposited till debris. The debris flows are traced laterally by seismic data and in shallow cores and have been correlated with till packages identified within the Norwegian Channel (King et al., 1996, 1998; Sejrup et al., 1996). The material of the debris flow was originally deposited at the shelf break in front of the NCIS during phases of shelf-edge glaciation and then subsequently reworked downslope by gravitational processes (King et al., 1998).

King et al. 1996	Nygård et al. 2005	Gen. Interpretation
Seq. 1-4	P1a-d	GDF
Seq. 5	P2	G.M?
Seq. 6 TS	P3 TS	Debrites
Seq. 6	P4a-c	Mainly GDFs
Seq. 7	P5	GDFs
Seq. 8	P6	Gravity Flow
Seq. 9 MS	P7 MS	Debrites
Seq. 9	P8	Mainly GDFs
Seq. 10 /11	P9 Sc	Debrites
	P10	GDFs

Fig. 2.6: North Sea Fan sequence stratigraphy (modified from Nygård et al., 2005). MS= Møre Slide, TS= Tampen Slide, G.M= Glaciomarine, GDF=Glacigenic debris flow.

Nygård et al. (2005) subdivided the proximal stratigraphy of the North Sea Fan into ten sequences with P1 as the youngest sequence and P10 as the oldest sequence (Fig. 2.6). Sequences P1, P4, P5, P6, P8, and P10 show glacigenic debris flow deposits and were formed by ice streams flowed through the Norwegian Channel (NCIS) during peak glaciation. P4, P5, P6, P8, P10 in the North Sea proximal part formed in the North Sea Fan during four different pre-Wichselian glaciations (Lee et al., 2012). P3 and P7 represent slide debrites that formed during the interglacial periods. P7 is the Møre slide and has age of MIS 12, approximately equal to 0.4 Ma, while P3 is formed by the Tampen slide during MIS 6 (Marine isotope stage), which is approximately equivalent to 0.2 Ma (Fig. 2.7). These sequences thin to zero across Møre Marginal High. P2 corresponds to the sequence 5 of King et al. (1999) and has low to medium amplitude reflector separating P2 and P1 (Sejrup et al., 2005) (Fig. 2.6).

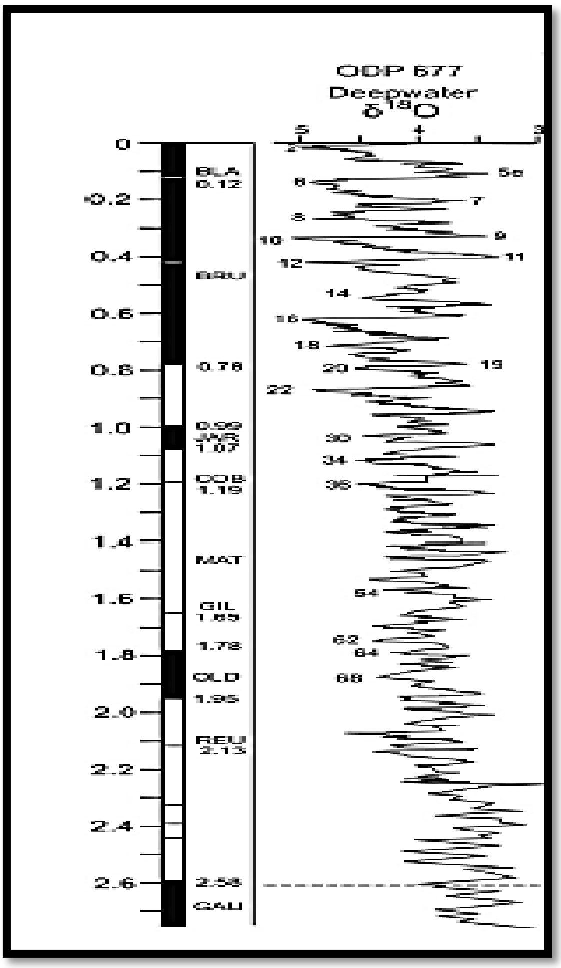

Fig. 2.6: Deep sea Oxygen 18 record along with the ages (Modified from Lee et al., 2012).

2.3.2 Norwegian Channel

The Norwegian Channel is a deep (200-700 m) offshore trench channel. It bends along the southwestern coast of Norway through Skagerrak and extends north to the continental margin west of Stadt and opens its mouth to the North Sea Fan (Sejrup et al., 1995; Lee et al, 2010). A glacial origin of the channel was considered by Sellvoll and Sunover (1974). More recent data demonstrate that it was created by the NCIS (Norwegian Channel ice stream) that flowed through this channel during several Quaternary glaciations. This channel provided sediments to a mouth fan (North Sea Fan). The channel is filled by glacigenic and marine sediments that get older towards the North Sea Fan (Sejrup et al., 2003) (Fig. 2.8). Evidence for the occupation of the Norwegian Channel by the Norwegian Channel ice stream deposits are obtains from the core 8903 within the Troll Field.

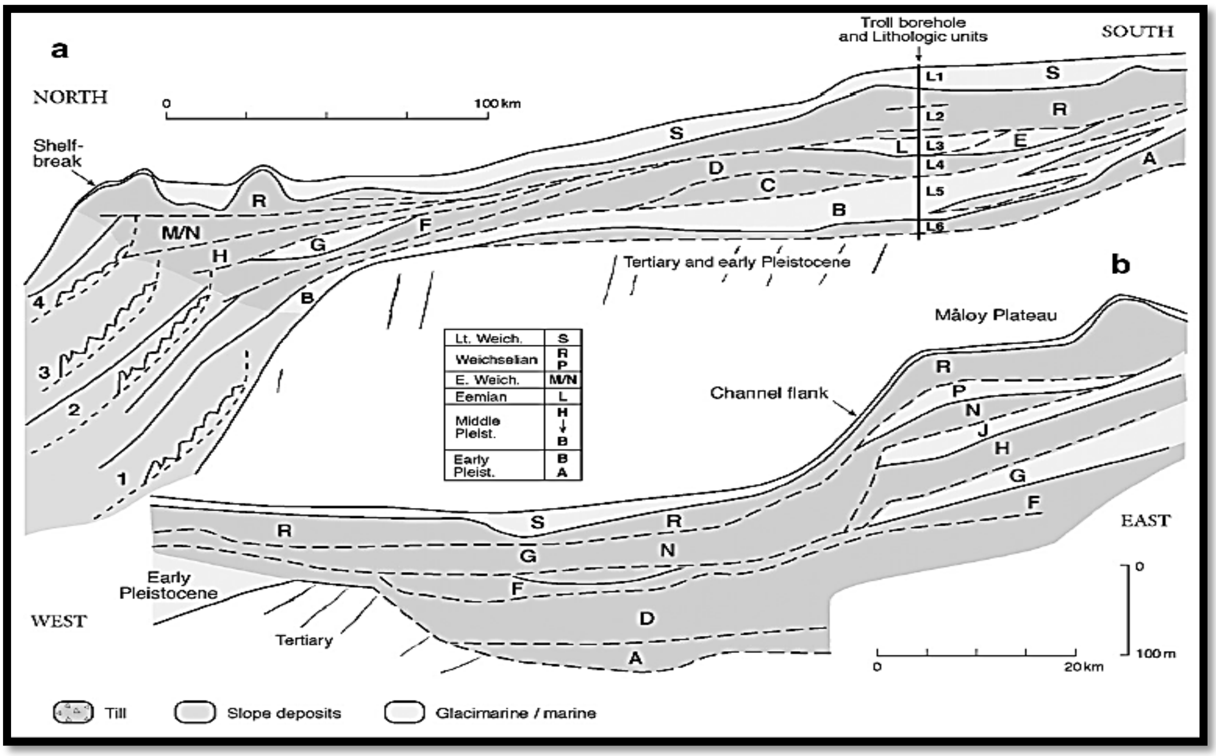

Fig. 2.8: Schematic cross-sections presenting the stratigraphy of the outer Norwegian Channel and North Sea Fan both parallel (a) and transverse (b) to the axis of the channel (from Lee et al., 2012).

Two pre-Weichselian glacigenic sediment packages are identified in the core 8903; the lower of which includes a till (L6) that has been constrained to an age of ca 1.1 Ma by amino-acid ratios, strontium isotopes, biostratigraphy and magnetostratigraphy (Sejrup et al., 1995). These till deposits belong to the Fedje Glaciation, the first shelf edge glaciation recorded. A marine sediment package overlies the Fedje Till deposits. This marine sediment package is of 40 m thickness and shows several arctic and temperate marine episodes.

Time span for deposition of this sequence is approximately 0.6 Ma between 1.1 and 0.5 Ma (MIS 34-13) (Sejrup et al., 1996; Lee et al., 2012). Two temperate marine events are picked out within core 8903. These events may belong to two interglacial periods, the Radøy Interglacial, and the Norwegian Trench Interglacial (Sejrup et al., 2000). Above the marine unit L4 of upper Middle Pleistocene present this till unit is believed to postdates of the Radøy Interglacial and is correlate able to MIS 12 (Fig.2.9).

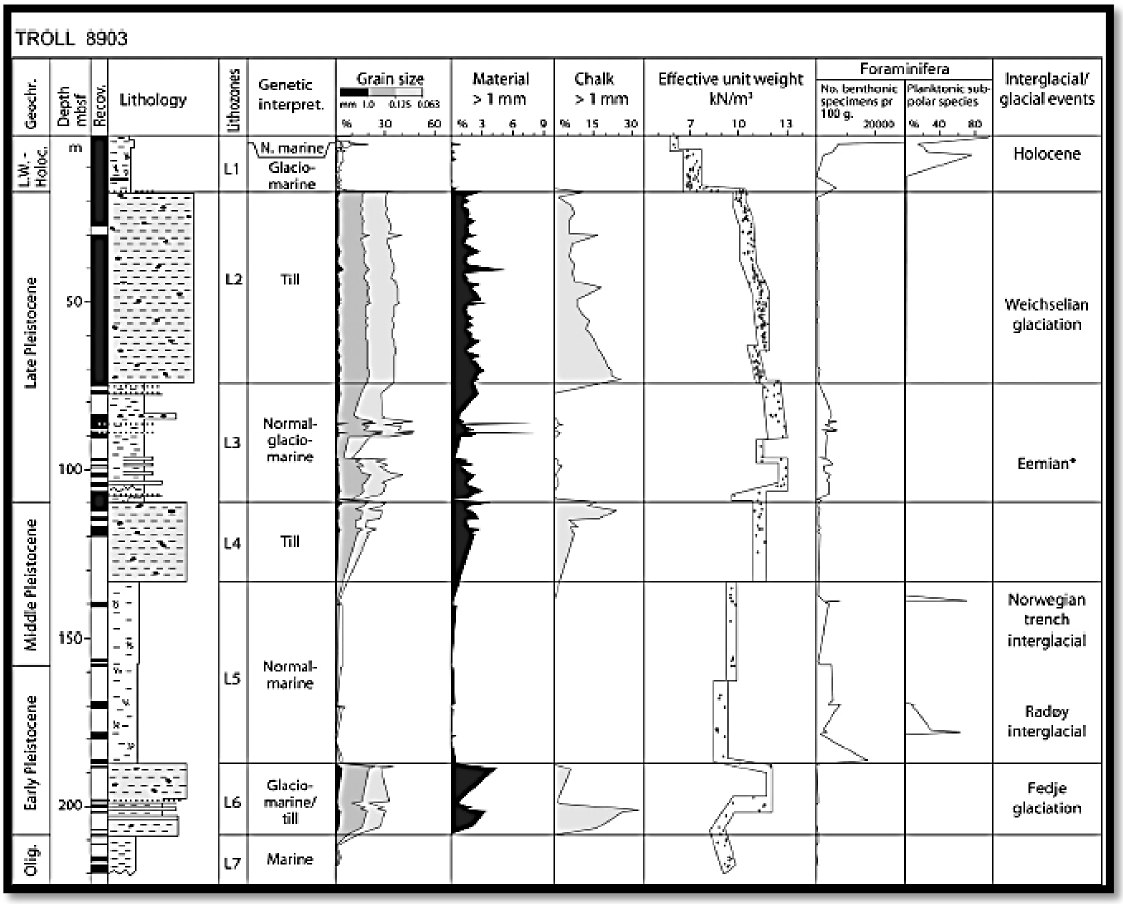

Fig. 2.9: The Quaternary succession of the Troll borehole (8903) with distribution of tills, glaciomarine and non-marine sediments and their chronostratigraphic interpretation (Lee et al., 2012).

Above the till unit L4 several post MIS 12 till-glaciomarine-marine sediment packages have also been recognized within the Norwegian Channel (and also in the Jæren lowlands) that can be identified on cores and seismic profiles (Sejrup et al., 1995, 1996, 2003; Janocko et al., 1997) (Figs. 2.9, 2.7).

3. Data and methods

Principles of seismic sequence stratigraphy applied on glacially formed glaciomarine deposits were used to interpret the multichannel 2D seismic reflection data in the present study.

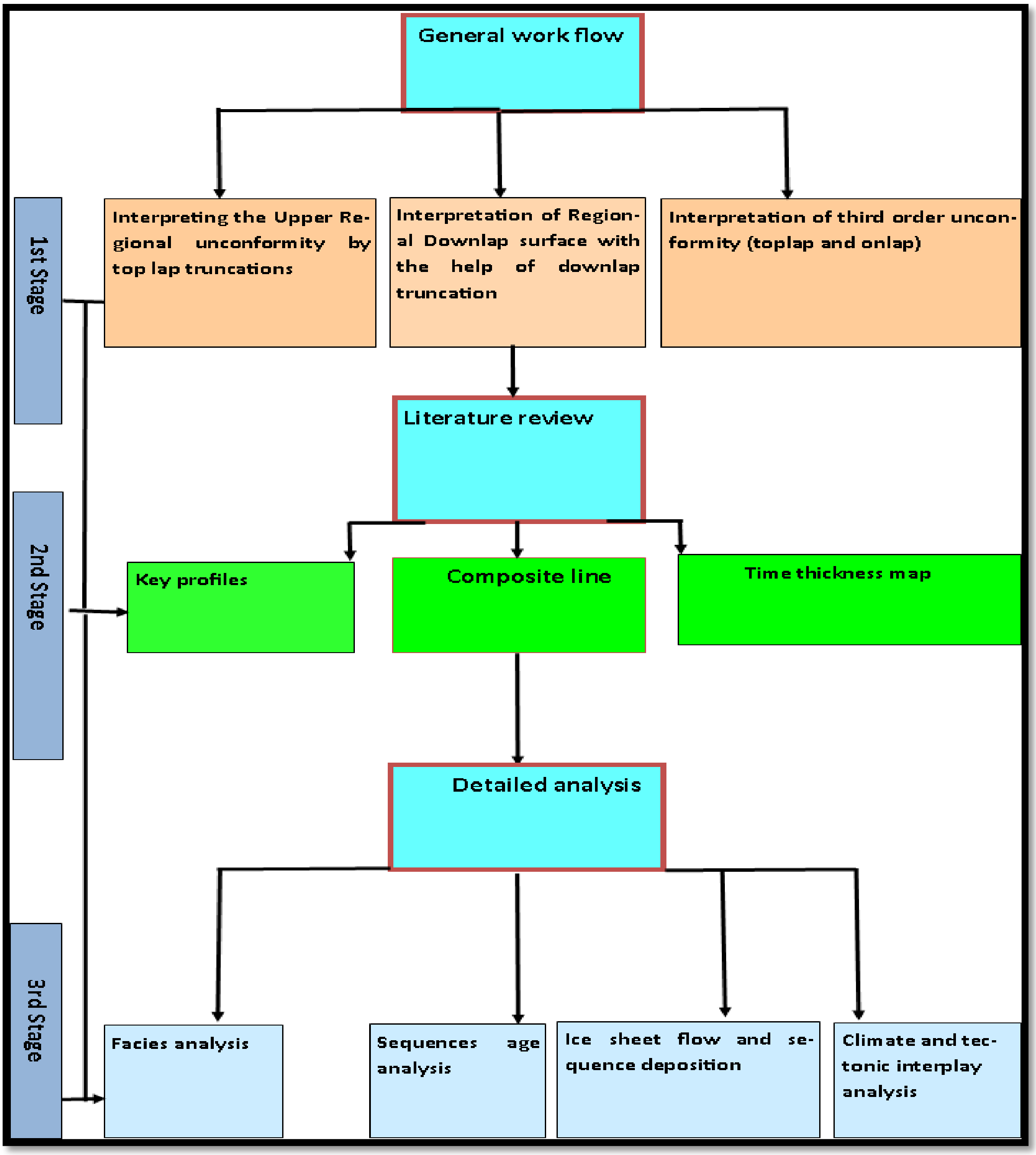

Fig. 3.1: General workflow that has been adopted.

A brief description of the methods that have been used to interpret the 2D seismic reflection data is given below

3.1 Sequence stratigraphy and sequence boundaries

Sequence stratigraphy is a widely used method of stratigraphic analysis applied to interpret processes and controlling factors of depositional systems, identification of systems tracts and formation of bounding surfaces; the method is applicable at different levels, depending upon the purpose of the study and the data available (e.g. geophysical, sedimentological, petrographic, e.t.c) (Catuneanu & Zecchin, 2012).

Sequence stratigraphy can be defined as the branch of geology that is used to define the sedimentary deposits into genetically related strata bounded by unconformities and their correlative conformities (Helland-Hansen et al., 2009).

Catuneanu et al., (2011, p. 184) applied the concept of sequence as "a cyclic change in the accommodation or sediment supply defined by the recurrence of the same types of the stratigraphic surface". This definition also includes the 'genetic stratigraphic sequence' defined by maximum flooding surface (MFS) (Galloway, 1989), the 'transgressive-regressive sequence (T/R-sequence)', applying the transgressive surface (TS) as sequence boundary (Embry 1993), as well as the 'depositional sequence' of the Exxon systematics defined by the subaerial unconformity (SU) and its correlative marine conformity as the sequence boundary (SB) (e.g. Posamentier et al., 1988).

Seismic sequence stratigraphy is a branch of sequence stratigraphy in which the sedimentary rocks are divided into different sequences on the basis of picking surfaces by onlap, toplap and downlap truncations. In the present study, sequence boundaries have been defined by using this method of recording lapouts (Fig. 3.2).

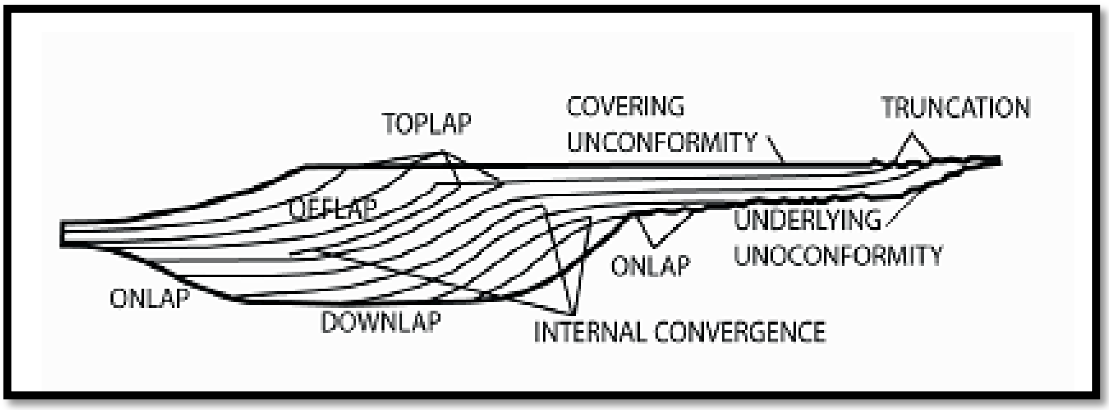

Fig. 3.2: Stratal terminations within a seismic sequence (after Mithum et al., 1977)

Seismic stratigraphic interpretation relies on the quality of the seismic data. The sesimic resolution is a main limiting factor for the application of a seismic sequence stratigraphic analysis, and both the vertical and the horizontal resolution are limiting factors due to the tuning effect and signal to noise ratio. Main controlling factors for sequence development include 1) rate of sediment supply, 2) rate of creation or destruction of accommodation space, and 3) rate in changes in relative sea level (Catuneanu 2011).

The sequence concept cited above from Catuneanu (2011, p.184) has been applied in the present study. Glaciomarine seismic sequences can be bounded by repetitive erosional unconformities and their marine conformities. In a shelf setting during glaciation, erosional unconformities can be formed beneath sea level from erosion at the base of a grounded ice sheet (Fulthorpe et al., 2004). Marine conformities may form as depositional surfaces in front of ice sheet margins or as flooding surfaces formed during interstadial and interglacial periods with mud and clay sedimentation (Laberg & Vorren, 2000).

In the study area, sequence boundaries formed as unconformities due to erosion from grounded ice sheets are picked by toplap truncations, erosional channels or onlap surfaces. The application of sequence stratigraphic principles in glociogenic deposits is more problematic than for normal paralic or shallow-marine deposits. This is due to the fact that changes in sea level during a glacial cycle are strongly influenced by the interplay of glacial advance and retreat and the resulting loading and rebound of the continental shelf (Ghali, 2005). The unconformities that are formed by glacial erosion are not easy to differentiate from those that are formed by subaerial exposure. The glacially eroded surfaces (unconformities) and the shelf succession resulted from glacial and glacial-related processess greatly depends upon paleo-water depth, ice sheet thickness, physical properties of sediments below the flowing ice sheet and ice sheet buoyancy (Laberg & Vorren, 2002).

According to Catuneanu and Zecchin (2013), high frequency sequences form primarily during cold ice-house periods, as parts of the Neogene and the Pleistocene, and display distinct stratal architecture as compared to those formed during warm green-house periods; sequences formed during cold periods are usually thin and show incomplete development of the systems tracts being dominated by transgressive deposits. In the present study area, high-frequency ‘cold’ sequences are assumed to attain greater thicknesses than in non-glacially influenced areas due to high rate of sediment supply from continental ice sheets.

3.2 Clinoforms and their pattern

Clinoforms are the basinward dipping bed boundaries that record palaeo-depositional surfaces that dip in basinward direction in an *en echelon* pattern, formed from basin progradation of a depositional clastic system (Mitchum, 1977; Vail, 1977).

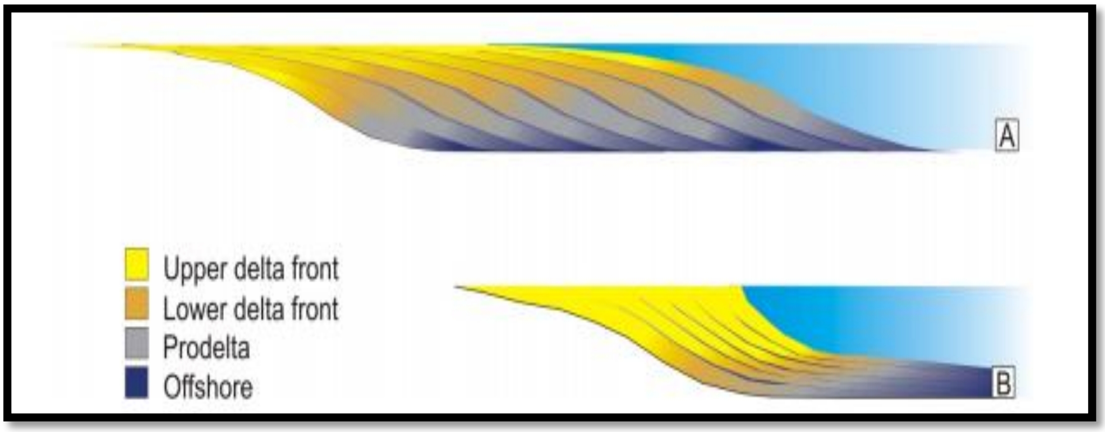

Fig. 3.3: (A) Sigmoidal clinoforms, (B) Oblique clinoforms; modified after Vail (1977); from Vassel, 2007.

Clinoforms have sigmoidal or oblique geometry. Sigmoidal clinoforms have topset, foreset and bottom set packages that indicate creation of accommodation or a constant accommodation throughout the progradation of the unit. Oblique clinoforms have foresets and bottomsets and indicate that the creation of accommodation space was reduced during sea level fall. Within the highstand system tracts clinoform geometry changes from sigmoidal to oblique recording destruction and/or infilling of accommodation (Vail, 1977) (Fig. 3.3). Helland-Hansen et al. (2009) defined clinoforms as shelf slope basin clinoforms, shoreline clinoforms and subaqueous delta clinoforms. A brief description of the geometry of clinoforms is shown in (Fig. 3.4).

The shelf slope clinoforms are important for the present study purpose. Clinothems, sediment packages bounded by clinoforms, deposited on the Mid-Norwegian continental margin in Neogene and Pleistocene time, give the present depositional architecture of the shelf, as revealed in seismic data. Shelf slope clinoforms may be hundreds of meter high and preserve details of the advancement of a shelf margin (Helland-Hansen et al., 2009).

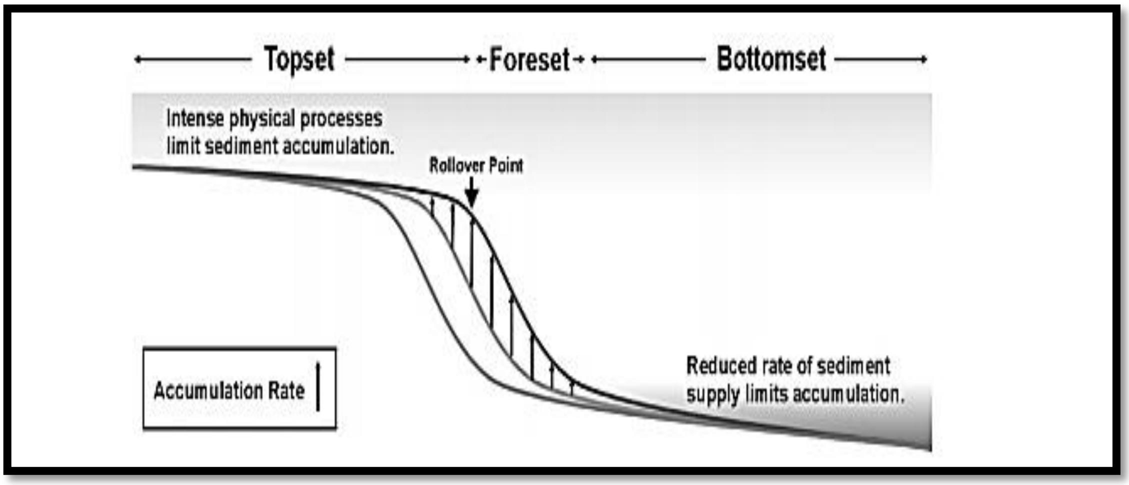

Fig. 3.4: Growth of clinoforms, topset, foreset and bottomset portions are indicated as well as the relative rate of the sediment accumulation and the rollover point (topset-foreset transition). No scale is provided to the figure as the clinoform are scale independent (after Wright & Friedrichs, 2006).

3.3 Trajectory analysis and sea level position

Offlap break trajectory analysis provides information about shelf migration and depositional environment (Bullimore et al., 2005).

Shelf migration is the function of changes in relative sea level, sediment supply, bathymetry and subsidence from loading and unloading. When there is great supply of sediments and less water depth, sediments prograde basinward (Bullimore et al., 2005; Helland-Hansen & Martinsen, 1996; Helland-Hansen et al., 2009).

The offlap break trajectories of clinoforms are divided into vertical ascending (positive), horizontal (flat), and vertical, descending (negative) offlap break trajectories. The trajectory trend direction describes the character of change in relative sea level during formation of the clinoforms (Helland-Hansen and Martinsen, 1996, Bullimore et al., 2005).

Positive offlap break trajectories form when there is a high rate of sediment supply relative to creation of accommodation space, and negative offlap break trajectories form when there is less supply of sediments as compared to the rate in creation of accommodation space. Horizontal, or flat offlap break trajectories, form when there is no change in sediment supply and creation of accommodation supply; the two factors are balanced (Fig. 3.5).

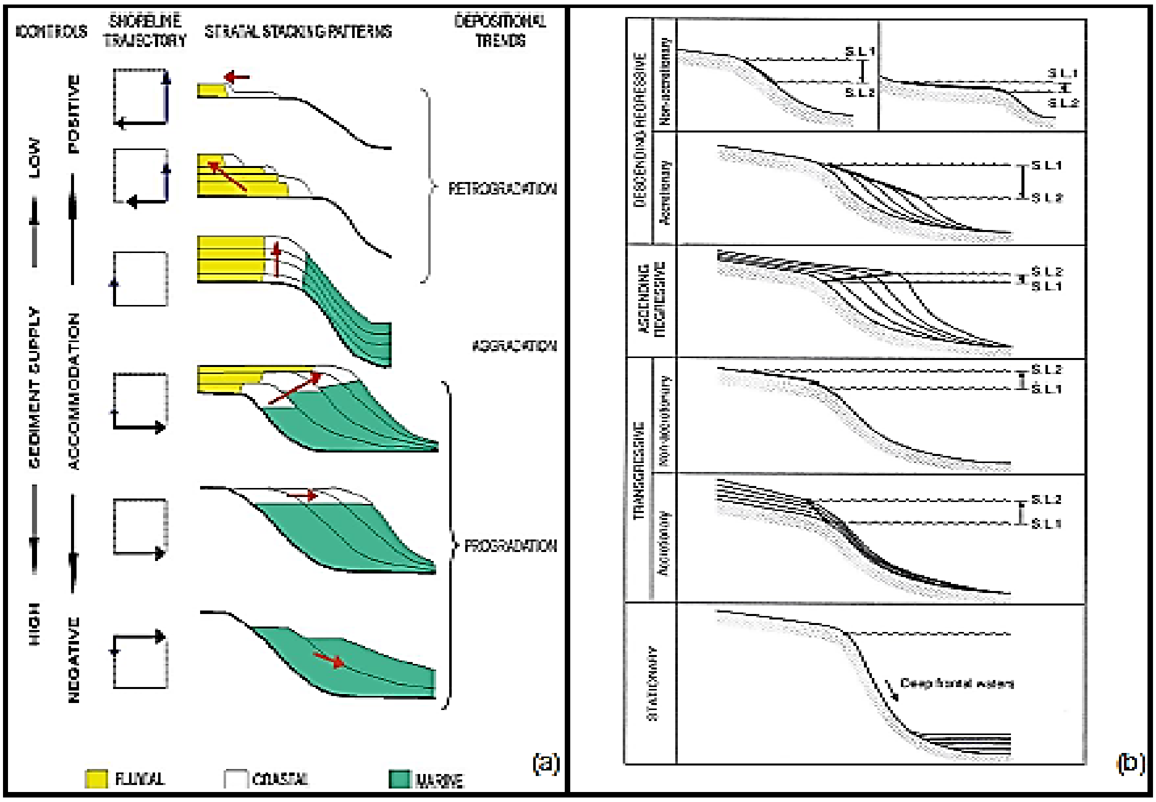

Fig. 3.5: a) Depositional trend with trajectory analysis (after Martins-Neto & Catuneanu, 2010). b) Shore line (or offlap break) trajectory classes (after Helland- Hansen et al., 2009).

3.4 Data

The data for the present study are multichannel 2D seismic reflection surveys in the northern North Sea and southern part of the offshore mid-Norway (Fig. 3.6). The data were acquired by different companies at different time. The data coverage is better in the southern part than in the northern part of the study area. The high resolution 2D seismic data were interpreted to mark the seismic surfaces on seismic interpretation software named Petrel-12 (product of Schlumberger). This is a complete open source seismic interpretation tool which allows visualizing and interpreting multi seismic data.

Data coverage along the dip lines is very good. Initially the seismic sections along the Mid-Norwegian shelf and the northern North Sea were interpreted and seismic sequence stratigraphic principles were applied to identify these seismic sections.

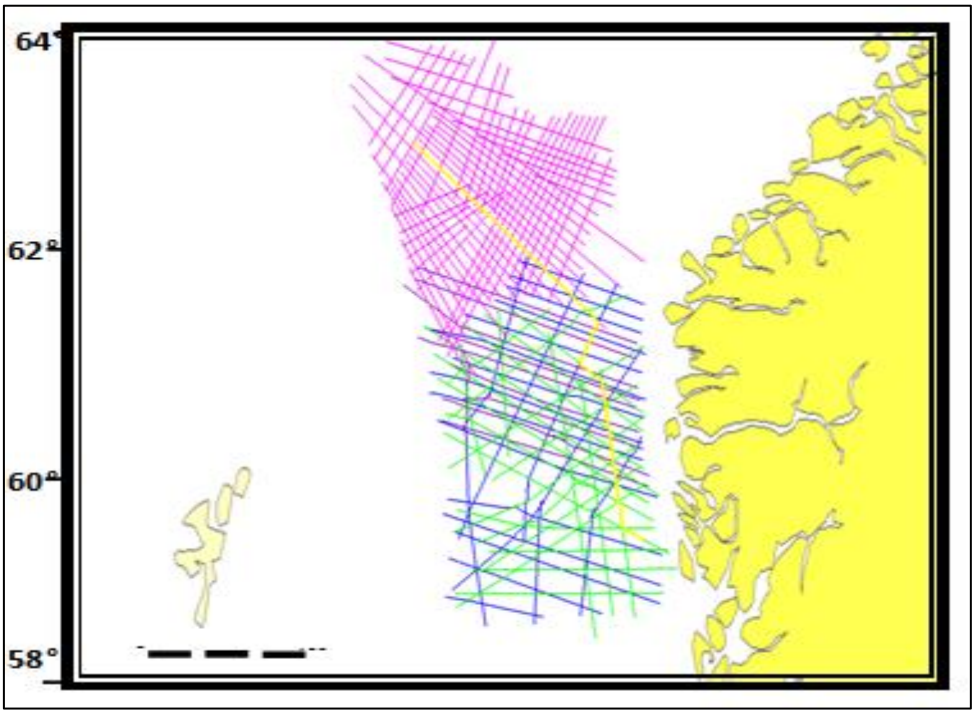

Fig. 3.6: Location of the data set that has been used for this study.

Some key lines were selected on the basis of the most optimal resolution and those that show the most distinct sequence stratigraphic configurations and clinoform development. After completing this analysis the attention was made on the area south of the Storegga slide, particularly the North Sea Fan area. The data coverage is dense in this area, with the 2D lines mainly oriented in NW-SW, NE-SW, NNW-SSE directions, but seismic lines with other orientations have also been applied. There is no single direct seismic line from the Norwegian

Channel to the North Sea Fan (NSF) area so the seismic lines from the Norwegian Channel to the North Sea Fan have to be tied up.

3.5 Methodology to interpret the seismic data and analyze the seismic sequences

The methodology that has been adopted to interpret the seismic data is as follow:

- First top lap truncations and downlaps were recorded on the prominent seismic lines of the upper regional unconformity (URU) and regional downlap surface (RDS), respectively. URU and RDS were thus marked on basis of these toplap truncations and downlaps. Fine sediments present at the RDS make it difficult to trace reflectors of sequence boundaries laterally in basinward direction.

- Subordinate unconformities are identified between the URU and RDS. These surfaces are interpreted by onlap and toplap (see above). On the basis of these surfaces, number of sequences has been observed along the Norwegian Channel. The interpreted surfaces of the dip lines are tied with the surfaces of strike lines to view the extension of the seismic sequences.

3.6 Facies analysis

Facies analysis is the next step after identification of sequences and includes delineation and interpretation of reflection geometry, amplitude, continuity frequency and interval velocity (Emery and Myers, 1996).

Seismic facies interpretation gives information about particular environmental conditions and geological setting. Mitchum et al. (1977, p. 121) defined seismic facies as “three dimensional mappable seismic unit that is composed of groups of reflections”. Facies identification is important to study palaeo-environment, climatic change and basin subsidence history (Catuneanu, 2006).

Seismic facies	Reflection configuration	Reflection continuity	Reflection amplitude and frequency	Bounding relationship	Depositional environment interpretation	Example (Vertical scale bars represent 100 ms)
1 Parallel continuous high amplitudes	Parallel	Continuous	High amplitude and low frequency	Continuous and draping underlying topography	Pelagic or hemipelagic	
2 Semiparallel continuous high amplitudes	Semiparallel	Continuous to semicontinuous	High amplitude and high frequency	Restricted to the top of the regional anticline	Debris flows or hyperconcentrated density flows or turbidites	
3 Mounded discontinuous low amplitudes	Contorted to mound-shaped	Discontinuous	Low amplitude and high frequency	Onlap, downlap, toplap, and truncation	Debris flows or (hyper) concentrated density flows	
4 Blocky semicontinuous high amplitudes	Oblique	Semicontinuous	High amplitude and high frequency	Separated by linear vertical to oblique surfaces	Lower slope and slumps or large lithified collapse blocks	
5 Oblique semicontinuous high amplitudes	Oblique	Semicontinuous	High amplitudes	Thinning out toward the platform	Upper slope	
6 Chaotic amplitudes	Chaotic	Discontinuous	Low amplitude	Grading vertically to facies 7 and laterally to facies 5	Platform interior	
7 Mounded semicontinous high amplitudes	Contorted to mound-shaped	Semicontinuous	High amplitude and low frequency	Numerous diffraction hyperbolas	Karstified platform top	

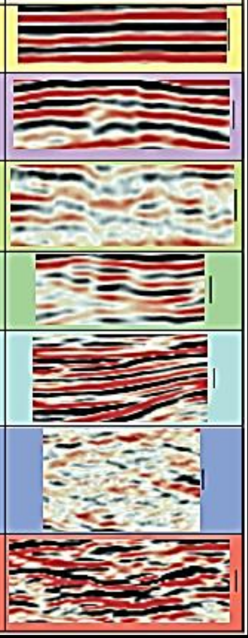

Fig 3.7: Different seismic facies along with their characteristic (after Janson et al., 2011).

Character of reflection pattern is important to reveal seismic facies information. Reflection configuration reveals information about lithology, type of stratification, depositional processes and environment. Different environments give rise to characteristic reflections, like prograding deltas with parallel topset and bottom set reflectors, while sigmoid or inclined reflectors represent foresets. Till and moraine deposits will show reflection free configuration with or without diffractions; diffractions are the response of boulder and larger blocks (Roksandic, 1978). Different types of reflection configurations are shown in Fig. 3.7.

3.7 Glacier dynamics as controlling factor on sequence formation

A glacier is a natural body of ice which is formed by accumulation, compaction, and recrystallization of snow. It is a dynamic system involving accumulation and transportation of ice. The movement of a glacier is critical and mainly depends upon temperature and gravity (Ben & Evans, 2010). Temperature conditions at the base of a glacier are particularly important as warm base glaciers have more erosional effect and movement than cold base glaciers. Ice sheets generally represent broad unconfined thick continental glacier ice that flow in irregular pattern. The part of an ice sheet where the flow is confined and fast compared to the remaining part of the ice sheet is called an ice stream (Martini et al., 2001). Continental ice caps influence on relative sea level changes and relative sea level generally during maximum of glaciation when sea level falls and during interglacial periods when sea level rises. Glacioisostatic rebound or uplift generally occur when the ice sheets melt during the warmer periods (Menzies, 1995).

In the present study glacier dynamics are considers very important to understand the depositional geometry of the sediments and formation of sequences. Miller (1996) stated that ice sheet thickness, buoyancy and relative sea level changes generally control the geometrical pattern in a shelf setting. The ice-flow models for the Scandinavian ice sheet during the late Weichselian has been reconstructed with the help of broad bathymetric data analysis together with preceding research on the Norwegian continental shelf (Vorren and Laberg, 1997) and on basis of Antarctic Ice Sheet and ice streams (Ottesen et al., 2001). Ice streams are generally belongs to the most extensive ice sheets, and capable of draining a tangible part of the ice masses (Bamber et al., 2000; Ottesen, 2006) see also discussion chapter.

The boundary at the shelf where the ice sheet starts to float generally depends upon ice sheet thickness and water depth and represents the buoyancy line. When an ice sheet starts to float, it does not erode, but start to accumulate its debris load (Berg et al., 2005). These factors upon formation of glacial cycles and sequences will be discussed further in later chapters.

4. Results

This chapter deals with the results that were acquired after careful interpretation on the 2D seismic line dataset. Initial part of this chapter will include the major horizons that were identified. After this, the chapter covers the results of the seismic sequences that were observed, then interpreted seismic facies, and at the end time thickness maps.

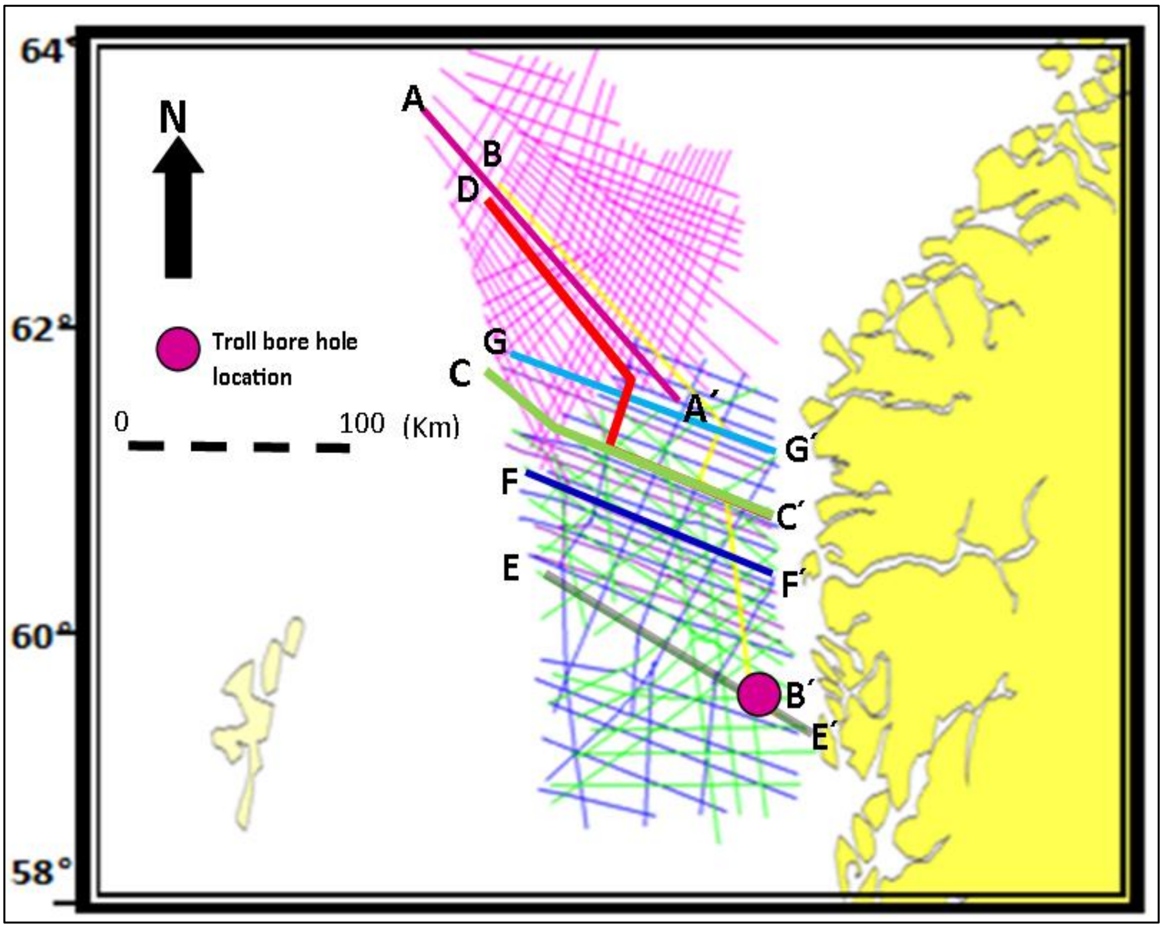

Fig. 4.1: Location of key seismic lines used in this study along with the location of the Troll borehole.

4.1 Seismic lines description

On the basis of identified seismic horizons, amplitude, continuity and nature of the bounding surfaces various seismic sequences have been identified. In Chapter 3 it was described that these elements generally represent particular sets of depositional environment for individual sequences.

The uppermost Cenozoic sediments are mostly made up of glacigenic debrites interbedded with marine and glaciomarine sediments of the Naust Formation on the mid-Norwegian continental shelf (Rise et al., 2005) and its likely equivalents south to Sognefjorden (Ottesen et al., 2009). The seismic sequences are described by their seismic signature. The main concern is the latest Plio-Pleistocene strata, these strata unconformably overly the Miocene or probably Pliocene rocks according to the new time scale, and the unconformity is the regional downlap surface, RDS. The RDS is made by the downlapping of the Naust Formation, as described in Chapter 2. RDS is very pronounced in the study area due to the impedance contrast between the glacial sediments above the surface and the underlying clay rich Miocene deposits (Reemst et al., 1996; Eidvin et al., 2000). The surface generally shows a smooth behavior throughout the study area. However, in the northern part of the study area the RDS is more irregular, being destroyed by mud intrusions. Hjelstuen et al. (2004) suggested an age of 2.7 Ma for this boundary on the basis of core data analyses, about the same age as suggested for the RDS below the Naust Formation on the mid-Norwegian shelf (Eidvin et al. 2000).

The strata which downlap onto RDS are truncated upward by the boundary called the upper regional unconformity (URU), which is very prominent in the eastern part of the area, compared to the western part. The upper regional unconformity is an angular unconformity with a wide regional extent. It can be traced in the seismic profiles by its overall planar nature. Some erosional features have been observed along the unconformity. This boundary indicates the change in depositional style from a strongly prograded succession below it to a aggrading succession above it. The Plio-Pleistocene succession can be divided into three megasequences on the basis of the depositional style. These are termed

- Megasequence I
- Megasequence NSF (North Sea Fan)
- Megasequence II (The North Sea Fan megasequence correspond to the megasequence II of the Norwegian Channel)

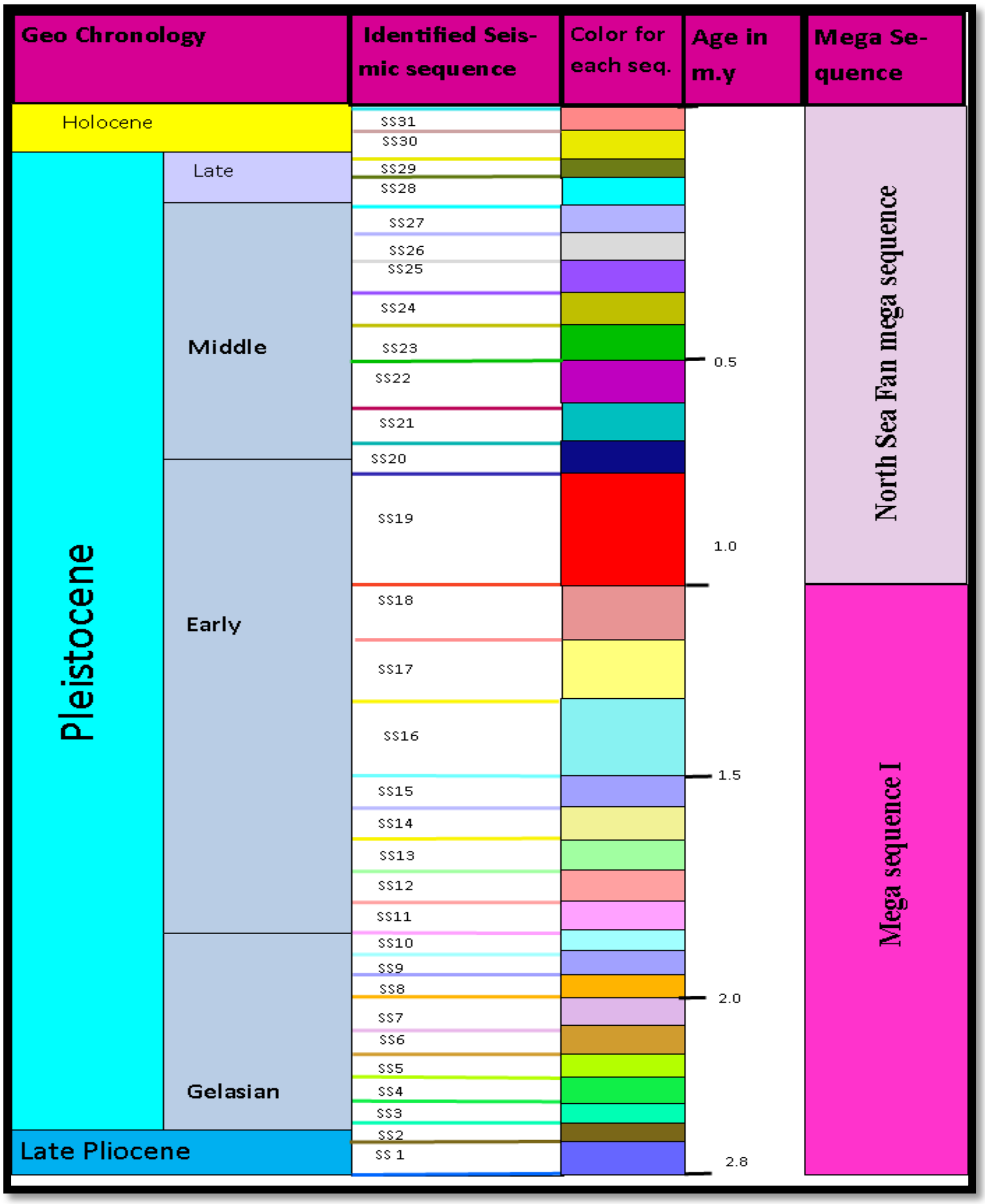

Fig. 4.2: Identified seismic sequences along with the megasequences. Seismic sequences 1 to 18 comprise the mega sequence I, while sequences above the megasequence I comprise the North Sea Fan mega sequence (This fig. is according to the new time scale).

Megasequence I mainly comprises sequences that have strongly prograding wedge geometry above the RDS (Fig. 4.2).

Megasequence NSF overlies megasequence I and comprises sequences that have prograding to aggrading nature (Fig. 4.2).

Megasequence II consists of aggrading sequences in the Norwegian Channel above the URU and is confined to the Norwegian Channel.

4.1.1 Seismic line AA´

This seismic line extends approximately 170 km from the southeastern to the northwestern part of the Møre Basin. The seismic line AA´ represents a general interpretation along the North Sea Fan area (Fig. 4.1).

The fan complex generally overlies the older succession in the Møre Basin and the Møre Marginal High and represents a large progradational wedge of glacigenic sediments (Blystad et al., 1995; King et al., 1996). These deposits have been formed at the shelf edge during glacial maxima and contain glacigenic debris flow deposits (GDFs), slide debrites and hemipelagic sediments (King et al., 1996). Glocigenic debris flow deposits were sourced directly from till deposits at the shelf break (Nygård et al., 2002; Sejrup et al., 1996).

Seismic sequence 23 is the Møre slide, while seismic sequence 27 is the Tampen slide. Tampen and Møre head walls are also shown in the (Fig. 4.3). The fan complex generally overlies the older succession in the Møre Basin and the Møre Marginal High and represents a large progradational wedge of glacigenic sediments (Blystad et al., 1995; King et al., 1996).

These deposits have been formed at the shelf edge during glacial maxima and contain glacigenic debris flow deposits (GDFs), slide debrites and hemipelagic sediments (King et al., 1996). Glocigenic debris flow deposits were sourced directly from till deposits at the shelf break (Nygård et al., 2002; Sejrup et al., 1996). Seismic sequence 23 is the Møre Slide, while seismic sequence 27 is the Tampen Slide. Tampen and Møre head walls are also shown in fig. 4.3.

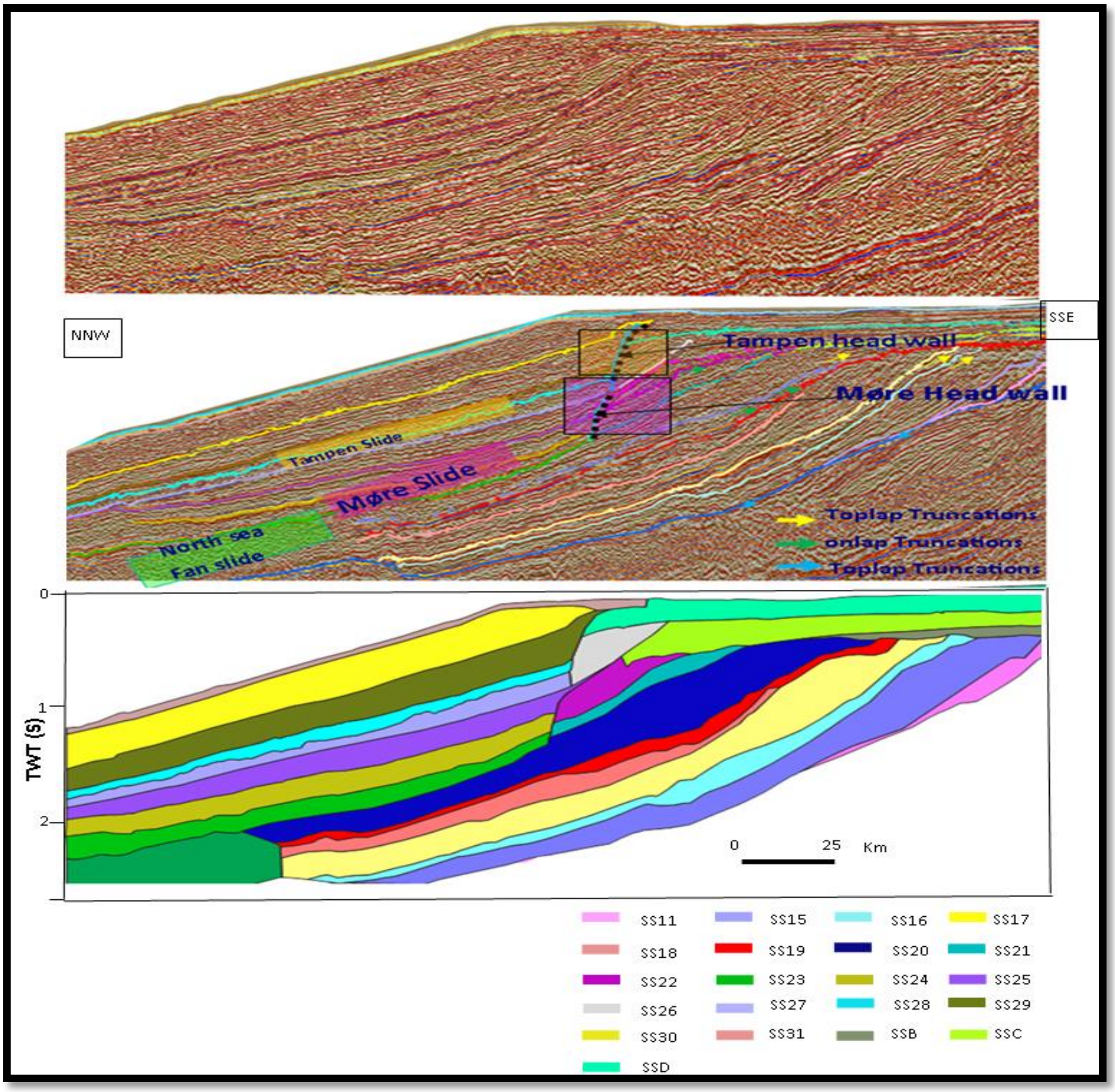

Figure 4.3: Seismic line AA´ (for location see figure 4.1)

4.1.2 Seismic line BB´

This seismic section generally shows a longitudinal profile along the Norwegian Channel from the Troll bore hole to the NSF (North Sea Fan) area. The seismic sequences 1, 2, 3, 4, 9, 10, 11, 12, 13 and 14 are not present along this profile (Fig. 4.4). These sequences may be eroded or have not been deposited in this area.

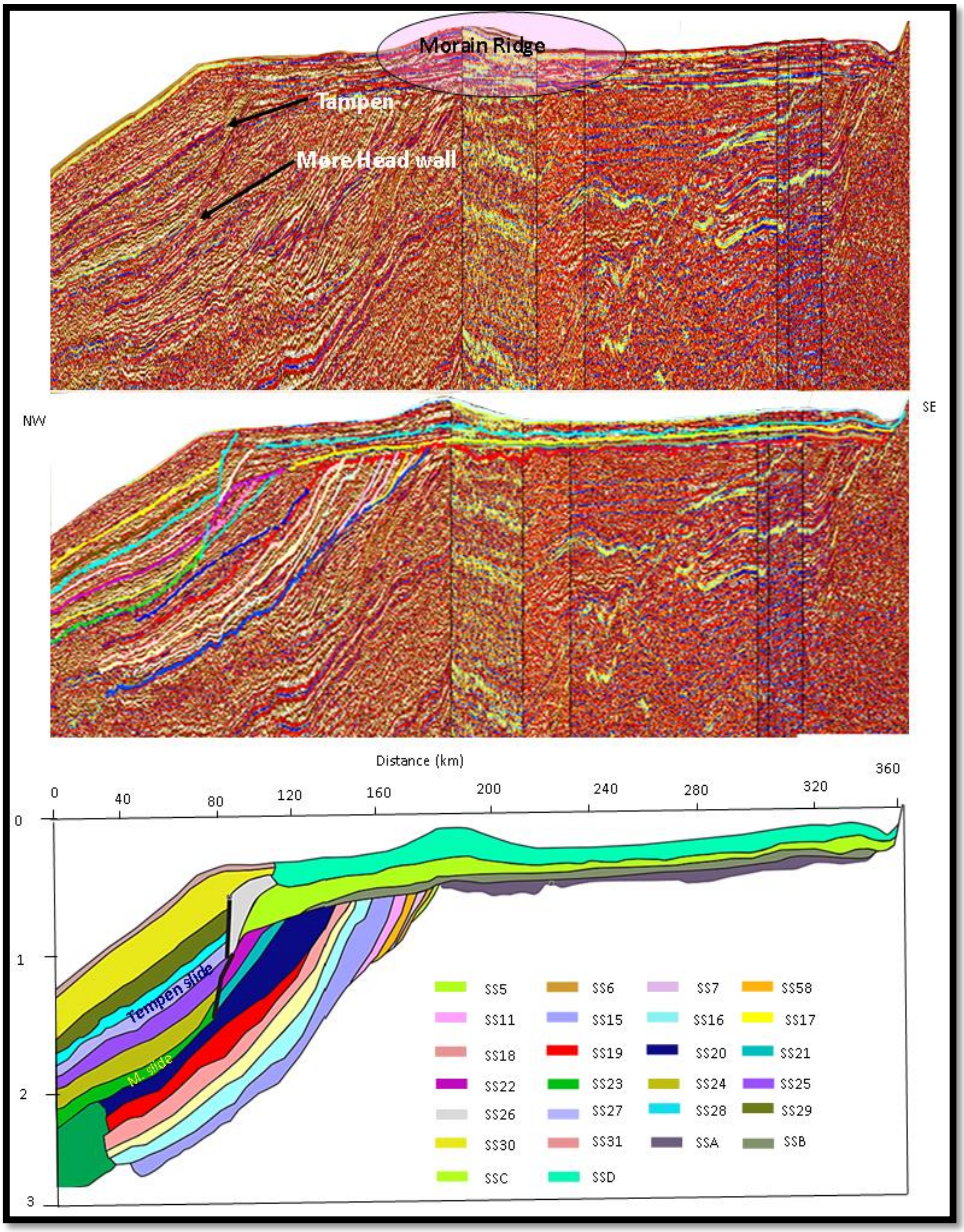

Fig. 4.4: Interpreted seismic line BB´ (for location see figure 4.1)**.**

4.1.3 Seismic line DC´

This seismic profile is located along the Norwegian Channel (Fig. 4.5).

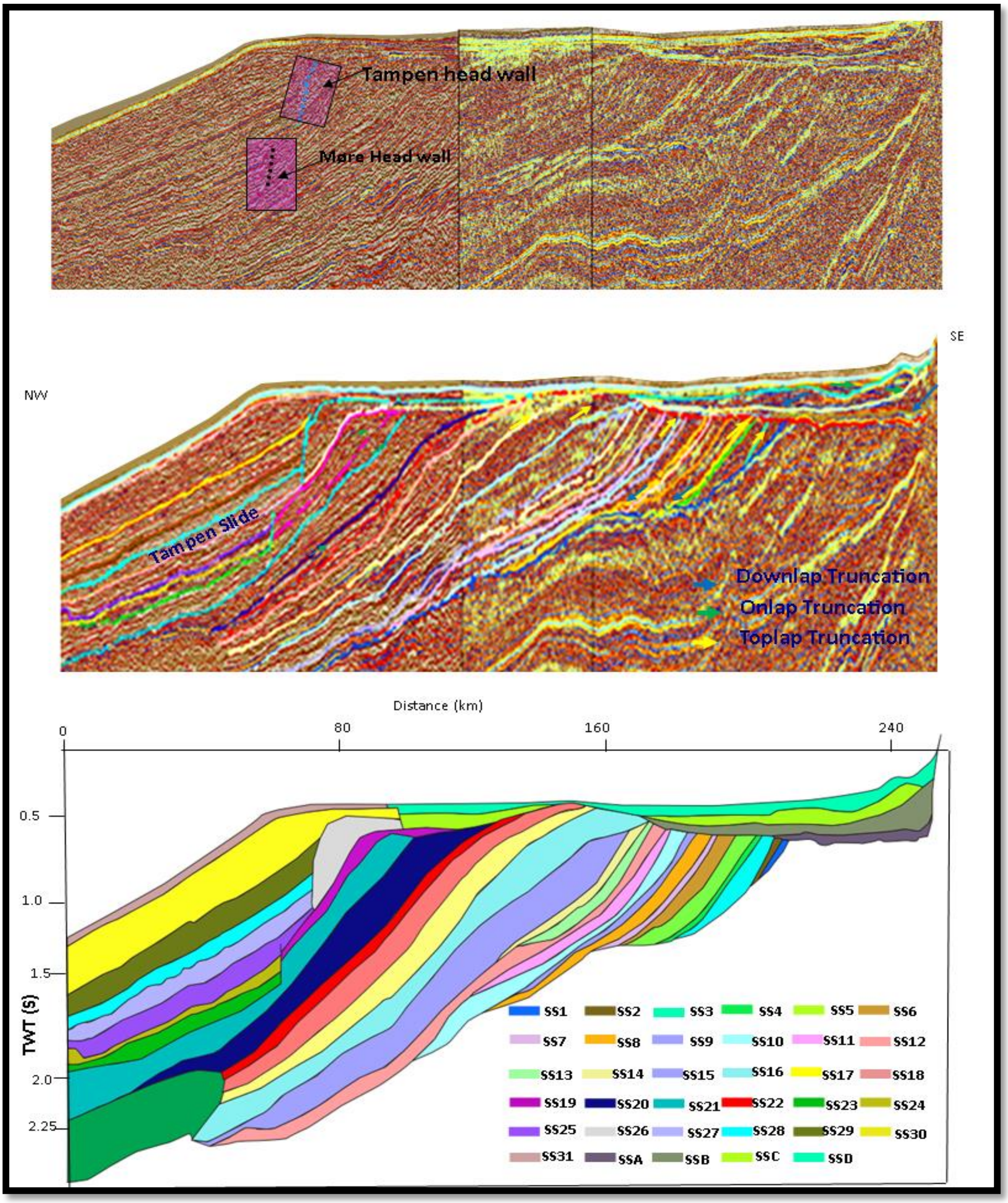

Fig. 4.5: Interpreted seismic line DC´ (for location see figure 4.1).

31seismic sequences along with the SS-A to SS-D sequences (megasequence II) in the Norwegian channel have been observed and correlated along this profile.

4.1.4 Seismic line CC´

This seismic section generally extends laterally up to 200 km from the southernmost margin of the Møre Basin and is oriented almost normally to the coast line.

It represents the type line and covers the central part of the study area. Almost all surfaces/unconformities are very well developed at this seismic line. On this line it is also comparatively easy to distinguish different seismic sequences. Along this seismic section the upper regional unconformity (URU) is characterized by maximum amplitude. URU is continuous in the eastern part of the study area, whereas the continuity of the URU decreases westward. Many erosional channels are present on the URU. These unconformity-related features are interpreted to represent the erosion made by glaciers (Fig. 4.6).

In addition to the upper regional unconformity many several local unconformities have also been observed along this profile at other stratigraphic levels. The seismic sequence boundary 16 represents an unconformity. The offlap break trajectories are descending (negative) (Fig. 4.6). The seismic sequences 12 and 10 show ascending (positive) offlap break trajectory (see Chapter 5).

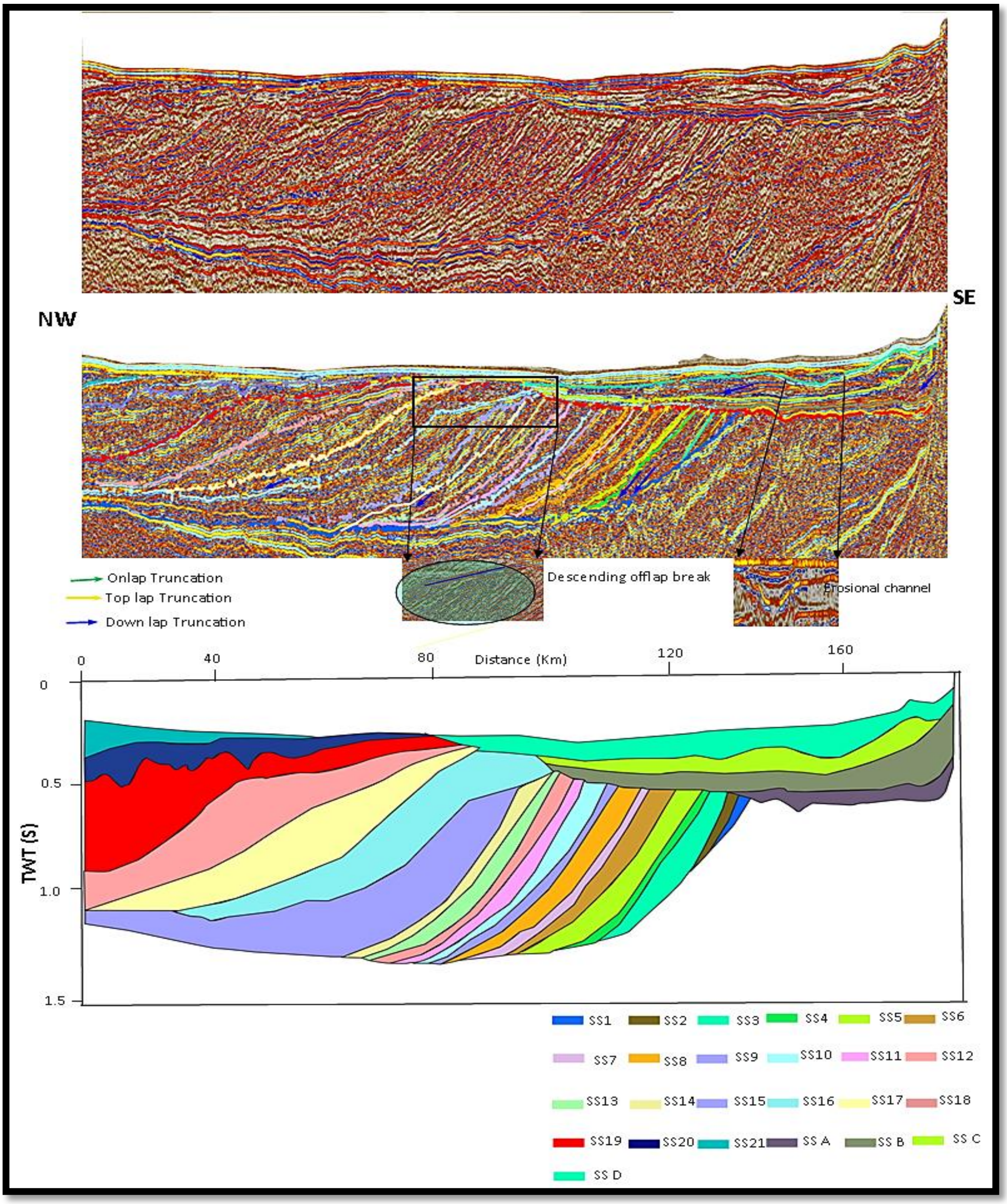

Fig. 4.6: Seismic stratigraphic interpretation along the line CC´ (for location see figure 4.1).

4.1.5 Seismic line FF´

FF´ profile is shown in Figure 4.1. The seismic sequences 1, 2, 11, 12, and 14 show the ascending offlap break trajectories which indicate fluctuation in sea level (Fig. 4.7).

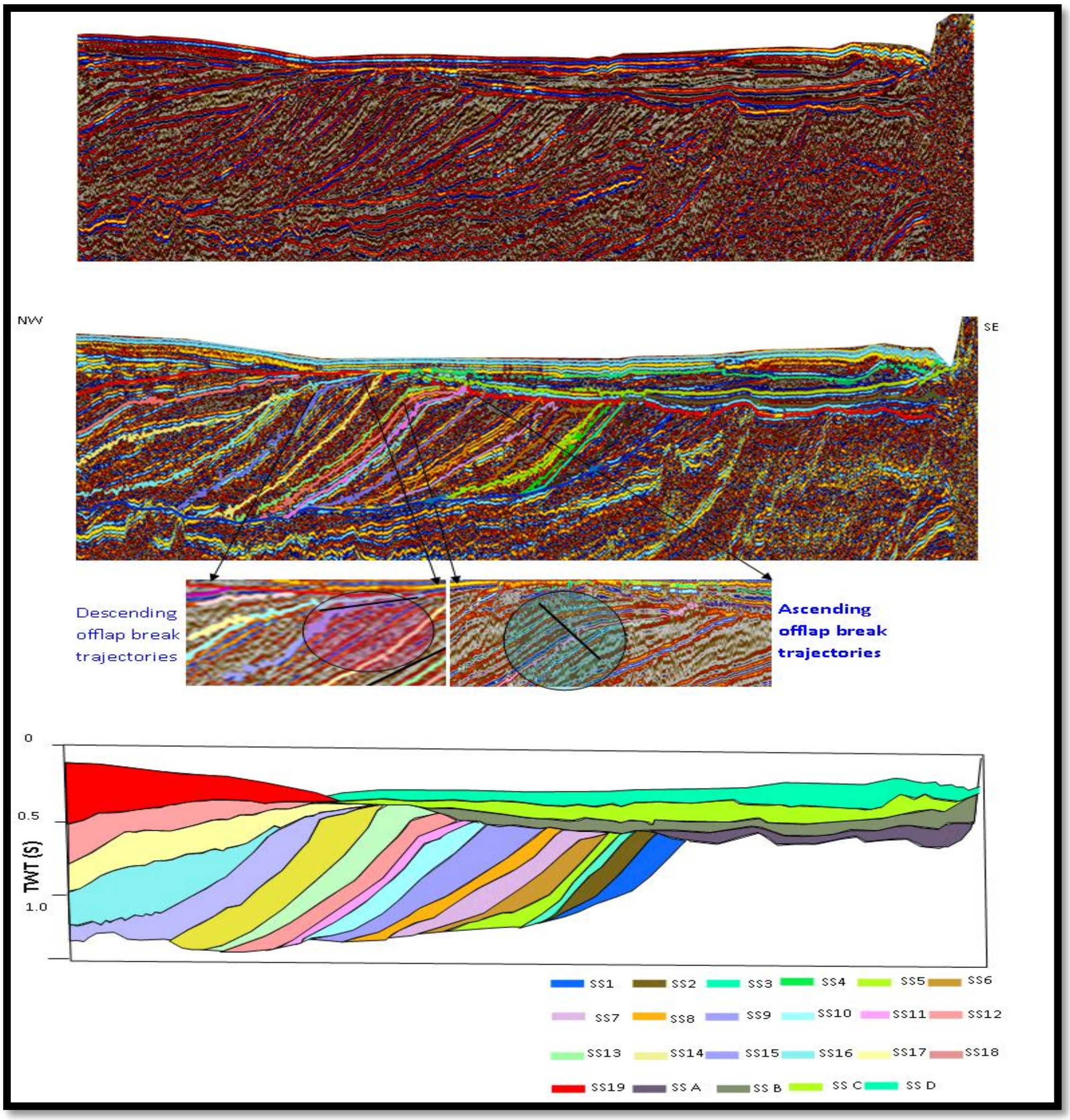

Fig. 4.7: Seismic stratigraphic interpretation along the profile FF´ (for location see fig. 4.1).

Seismic boundaries, unconformities and offlap break trajectories are prominent in this seismic line. The seismic line generally extends southeastward to Sognefjorden.

4.1.6 Seismic line EE´

This seismic line generally shows the seismic interpretation along the Troll borehole's side and is oriented normal to the Norwegian channel.

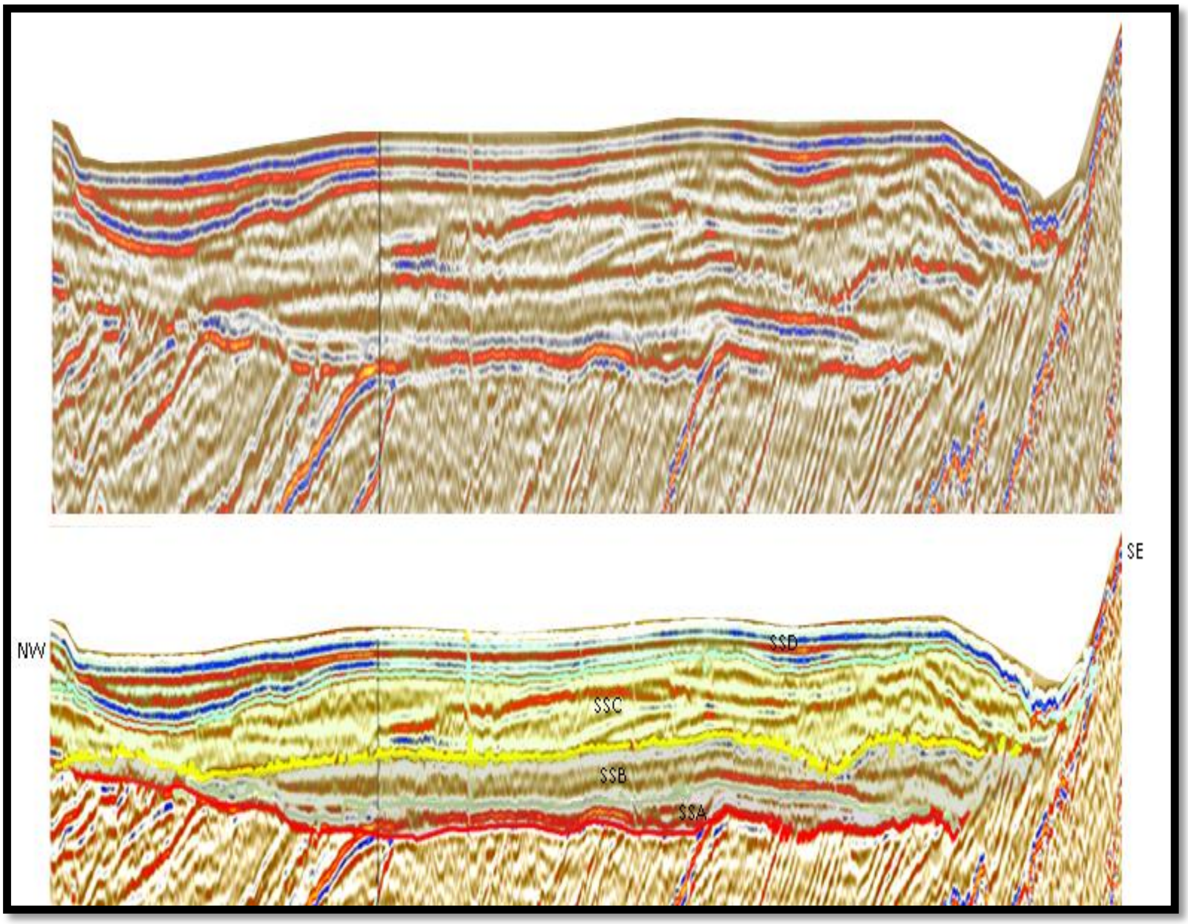

Fig. 4.8: Seismic interpretation along the seismic line EE´ (for location see Fig. 4.1).

Four seismic sequences have been interpreted above the unconformity (URU) (Fig. 4.8). These sequences are usually horizontal to sub-horizontal. Many erosional unconformities are present, and these confine to the sequence boundaries.

4.2 Description of sequences

4.2.1 Megasequence I

Megasequence I consists of the seismic sequences from 1 to18. These sequences and hence, the megasequence, are truncated by erosional unconformities that together form composite erosional unconformities in the coastal direction and correlative conformities in deeper part of the basin (Fig.. 4.2) (cf. Chapter 3).

Seismic sequence 1 (SS 1)

This seismic sequence has its lower boundary 1 coinciding with the RDS, while the upper boundary is defined by the seismic sequence boundary 2 (Figs 4.6 and 4.7). This seismic sequence is the lowermost seismic stratigraphic sequence of the succession that Ottesen et al. (2009) correlated with the Naust Formation. The clinoforms show oblique sigmoidal geometry. The topset is truncated by the upper regional unconformity, but in some seismic profiles this truncation is not very prominent, as seen from the presence of the offlap breaks. SS1 has not been recorded in the North Sea Fan area (Figs. 4.3 and 4.4).

Seismic sequence 2 (SS2)

The lower boundary is defined by the sequence boundary SS2 and the upper boundary by the sequence boundary 3. SS2 has oblique tangential geometry. This seismic sequence has the same character as SS1 (Figs 4.6 and 4.7). It has not been recorded in the North Sea Fan area (Fig. 4.4).

Seismic sequence 3 (SS3)

The lower boundary is marked by the SS3 sequence boundary, while the upper boundary is marked by the SS 4 seismic boundary. This sequence shows oblique tangential geometry and has steeper clinoforms than the previous seismic sequence (Figs. 4.6 and 4.7). This seismic sequence is truncated by URU. This seismic sequence has not been observed in the North Sea Fan area (Fig 4.3).

Seismic sequence 4 (SS4)

The lower boundary is defined by the SS4 sequence boundary and the upper boundary is defined by the SS5 seismic boundary (Fig. 4.6). The sequence is truncated by URU and has oblique tangential geometry. SS4 was not deposited in the North Sea Fan area (Fig. 4.4).

Seismic sequence 5 (SS5)

Seismic sequence 5 is defined by the SS5 and SS6 sequence boundaries at its lower and upper boundary surfaces, respectively. It has an oblique tangential geometry, and topsets of this seismic sequence are truncated by the upper regional unconformity (URU). The SS5 has high amplitude sub-continuous reflectors, whereas chaotic reflection pattern is very prominent in the distal part of the sequence (Fig. 4.6).

This seismic sequence has been recorded in the North Sea Fan area and generally has the wedge shape prograding appearance with some high amplitude reflectors and there it overlies the regional downlap surface (Fig. 4.4).

Seismic sequence 6 (SS6)

Sequence boundaries 6 and 7 define the lower and upper boundaries of this seismic sequence, respectively. This seismic sequence has the oblique clinoform geometry and generally medium to high amplitude reflectors which are parallel to sub-parallel in character comprise the sequence (Figs. 4.6, 4.7).

In the North Sea Fan area SS6 is generally present in the form of an oblique prograding wedge and with medium amplitude reflectors (Fig. 4.4).

Seismic sequence 7 (SS7)

The SS7 and SS8 sequence boundaries define the lower and upper boundary surfaces, respectively, of this sequence. This seismic sequence holds oblique tangential geometry (Fig. 4.6). In the North Sea Fan area the seismic sequence has oblique progradational geometry (Fig. 4.4).

Seismic sequence 8 (SS8)

SS8 is defined at the base by the SS8 sequence boundary and the upper boundary is terminated by the SS9 sequence boundary. The sequence shows oblique sigmoidal geometry. Medium to low amplitude discontinuous reflectors are present with chaotic reflection and more chaotic behavior in the basinward direction (Figs. 4.6 and 4.7). SS8 is present in the North Sea Fan area and shows oblique clinoforms geometry, but shows almost similar reflector behavior appearance as in southern part of the study area (Fig. 4.4).

Seismic sequence 9 (SS9)

SS9 is bounded by the sequence boundary 9 at the base and the sequence boundary 10 at the top. Top sets are truncated by the upper regional unconformity, giving the oblique geometry. This seismic sequence generally shows structureless seismic facies with more chaotic reflection in the distal basinward side (Fig. 4.6). The seismic sequence has not been recorded in the North Sea Fan area (Fig. 4.4).

Seismic sequence 10 (SS10)

This sequence is defined by the seismic sequence boundary 10 and the seismic sequence boundary 11, forming the lower and the upper boundaries, respectively. SS10 has medium to low amplitude discontinuous reflection with oblique sigmoidal geometry (Figs. 4.5, 4.6 and 4.7). This sequence is not present in the North Sea Fan area (Fig.4.4).

Seismic sequence 11 (SS11)

The lower boundary is defined by the SS 11 sequence boundary, while the upper boundary is defined by the SS 12 sequence boundary. In the southern part of the study area, this sequence is comprised of medium to high amplitude reflectors, and the reflectors are parallel to sub-parallel in the proximal side, at the distal side the reflector pattern is more chaotic (Fig. 4.6).

In the North Sea Fan area this seismic sequence is present in the form of a progradational wedge with medium to low amplitude reflector (Fig. 4.4).

Seismic sequence 12 (SS12)

The SS12 and SS13 sequence boundaries define the lower and upper bounding surfaces, respectively, of this seismic sequence. The sequence is a wedge shaped progradditional sequence and has high amplitude parallel and continuous to discontinuous reflectors. Topsets are not eroded completely, some offlap breaks are preserved, and the offlap break trajectories show the ascending offlap break character (Figs. 4.6 and 4.7). SS 12 is present in some seismic profiles of the North Sea Fan area, but is not present in the line BB´ (Fig. 4.4).

Seismic sequence 13 (SS13)

The lower and upper boundaries of the seismic sequence are defined by the SS13 and the SS14 sequence boundaries, respectively.

The seismic sequence has oblique sigmoidal geometry (Fig. 4.6). This sequence has not been recorded in the North Sea Fan area (Figs. 4.3 and 4.4).

Seismic sequence 14 (SS14)

The lower boundary is defined by the SS 14 sequence boundary, while the upper boundary is defined by the SS15 sequence boundary. This seismic sequence shows oblique sigmoidal geometry and has not been recorded in the North Sea Fan area (Figs. 4.3 and 4.4). The sequence boundary 15 is a local downlap surface (Fig. 4.6.).

Seismic sequence 15 (SS15)

The lower boundary of the sequence is defined by the sequence boundary 15, while upper boundary by the sequence boundary 16. The seismic sequence is composed of parallel reflectors which converge upward and are truncated by the upper regional unconformity. The distal basinward part of the sequence contains the mounded reflection pattern that may be due to high clay content at the base (Fig. 4.6).

The sequence is present in the North Sea Fan area and has medium to lower amplitude reflectors. Mounded facies is also observed in the toe side of the sequence (Fig. 4.4).

Seismic sequence 16 (SS16)

The sequence boundary 16 which is the local downlap surface defines its lower boundary while the upper boundary is defined by the sequence boundary 17. The sequence boundary 16 defines an unconformity that developed on the large lateral scale.

After this there is a change in depositional style of the glaciomarine succession in the area, from high progradational style to less progradational style. Sequence boundary 16 is clear in the southern part of the study area. Clinothems are truncated upward by the upper regional unconformity, thus giving rise to the oblique clinoform geometry to this sequence (Figs. 4.6 and 4.7). The shelf was migrated to somewhat 70 km during the deposition of this sequence, and the seismic boundary 16 is curvilinear and tilted (Fig. 4.6). The sequence has a regional extension in the North Sea Fan area. In the North Sea Fan area the sequence contains the lens patches of high amplitude facies (Figs. 4.3 and 4.4).

Seismic sequence 17 (SS17)

SS17 is bounded below by sequence boundary 17 and above by sequence boundary 18.
This sequence has sigmoid-oblique prograding geometry of clinothems with parallel to sub parallel, high to medium amplitude reflectors with gently dipping clinoforms. Chaotic reflection is present at the distal part of the sequence. Offlap break trajectories show an ascending pattern (Fig. 4.6). In the North Sea Fan area this sequence has uniform thickness (Fig. 4.4).

Seismic sequence 18 (SS18)

The lower boundary of SS18 is defined by the sequence boundary of SS18, and the upper boundary is defined by the sequence boundary 19.

Mounded facies are present at the toe side of the sequence. Off lap break trajectories trend generally show the ascending character (Fig. 4.6). In the North Sea Fan area this sequence has the more or less uniform thickness and has the mounded facies at the distal (Fig. 4.4).

4.2.2 NSF (North Sea Fan) megasequence

Seismic sequence 19 (SS19)

The lower boundary of the sequence is defined by the sequence boundary 19, while the sequence boundary 20 defines its upper boundary. In the southern part of study area offlap break trajectories show the descending character. The strong amplitude horizontal reflectors are present at the upper side of this sequence, but changes in low to medium amplitude discontinuous reflectors laterally (Fig. 4.6).

Seismic sequence 20 (SS20)

SS20 is bounded by sequence boundary 20 at the base and seismic sequence boundary 21 at the top. Many incision channels are present at the sequence boundary 20. This seismic sequence contains less prograding clinoforms than the previous sequence. The chaotic reflection is more prominent in the slope and in the distal part of the area (Fig. 4.6).

Seismic sequence 21 (SS21)

SS 21 is bounded below by the sequence boundary 21 and the sequence boundary 22 above. The sequence is relatively thin and consists of less flat-lying sequences that onlap onto the lower boundary. The lateral extent towards the west is limited by the Møre slide head wall (Figs. 4.3 and 4.4).

Seismic sequence 22 (SS22)

The clinothems of SS22 onlap onto the lower boundary which is the sequence boundary 22 and in the southern part this sequence is composed of more or less aggrading units (Fig. 4.6). The sequence shows strong to medium amplitude reflection pattern (Figs. 4.3, 4.4 and 4.5).

Seismic sequence 23 (SS23)

The lower sequence boundary is defined by the sequence boundary 23 and the upper boundary is defined by sequence boundary 24 (Figs. 4.2 & 4.3).
This sequence comprises debrite sediments and has been called the Møre Slide by King et al. (1996) and Nygård et al. (2005). This sequence is 80 ms thick in the axis of the Fan and pinches out across the Møre marginal high (Figs. 4.3 and 4.4).

Seismic sequence 24 (SS24)

Sequence boundary 24 acts as its lower boundary, while the sequence boundary 25 is the upper boundary. The sequence is comprised of low amplitude to transparent facies. The sequence maintains the uniform thickness of about 250 ms twt. Towards the east it is limited by the steep slide head wall. The low amplitude character of the facies is interpreted to reflect mud of hemipelagic origin (Nygård et al., 2005) (Figs. 4.3 & 4.4).

Seismic sequence 25 (SS25)

This sequence is bounded by sequence boundary 25 and 26 as the lower and upper bounding surfaces, respectively. The sequence is characterized by low to medium amplitude facies, and the stacking geometry gives the mounded shape which indicates debris flow deposits (Figs. 4.3 & 4.4).

Seismic sequence 26 (SS26)

The lower boundary of the sequence is defined by sequence boundary 26. This sequence shows an acoustically transparent behavior and is easily distinguishable on all seismic profiles due to its unique character. It is a tongue shaped sequence than thins in basinward direction and is terminated by the head wall of the Tampen Slide in landward direction. Some medium to high amplitude reflectors are present at the upper side of the sequence. The sequence is equivalent to P4 of Nygård et al. (2005), which comprises mainly of glacigenic debris flows deposits and proposed that its upper surface has been eroded by P3 which represent to the SS 27 here (Figs. 4.4 & 4.5).

Seismic sequence 27 (SS27)

The lower boundary of this sequence is sequence boundary 25 and the upper boundary is sequence boundary 28.

This sequence is characterized by structureless facies and has been called the Tampen slide by King et al. (1996). The sequence contains slide debrites which give the structure less appearance. It is boundaryed by the Tampen head wall in the eastern side and has uniform thickness through with in the study area (Figs.4.3 & 4.4).

Seismic sequence 28 (SS28)

The lower boundary is defined by sequence boundary 28 while the upper boundary is defined by sequence boundary 29. Sequence boundary 28 has an undulating shape. SS28 is characterized by transparent and low amplitude stratified reflectors. The eastern extent is limited by the Tampen head wall. Thickness remains constant within the study area.

SS28 is equivalent to the sequence P2 of Nygård et al. (2005) and a marine/glaciomarine origin was suggested by these authors for the sequence (Figs. 43, 4.4 & 4.5).

Seismic sequence 29 (SS29)

The lower bounding surface of SS29 is defined by sequence boundary 29 and the upper bounding surface by sequence boundary 30 (Figs. 4.3 & 4.4). This seismic sequence is characterized by transparent and low to medium amplitude reflectors which are stacked upon each other and holds the uniform thickness throughout (Fig. 4.4).

Seismic sequence 30 (SS30)

The sequence is bounded by sequence boundary 30 and by sequence boundary 31 at the top. The internal reflection pattern of this seismic sequence is similar to the sequence SS29, but has more stacked mounded facies. It has more uniform thickness and pinches out in the landward direction (Figs. 4.4 & 4.5).

Seismic sequence 31 (SS31)

Lower boundary of this sequence is sequence boundary 31. It is the youngest seismic sequence and shows the medium amplitude reflectors and has the smaller thickness than the earlier sequences (Figs. 4.3 & 4.4).

4.2.3 Megasequence II

Usually horizontal to sub-horizontal stratal packages are grouped in the aggrading megasequence II and occurred in the Norwegian Channel. The North Sea Fan megasequence and its sequences SS19-31 corresponds to megasequence II of the Norwegian Channel (Lee et al., 2012). There are the following seismic sequences that have been observed in the Norwegian Channel.

Seismic sequence A (SS-A)

SS-A is very thin and is present at the upper regional unconformity. Its lower boundary SS-A coincides with URU. The upper boundary is marked by sequence boundary SS-B. It is generally present in the form of thin lenses directly above the upper regional unconformity and pinches out westward (Fig. 4.8).

Seismic sequence B (SS-B)

This sequence lies almost parallel above the SS-A and is bounded below by sequence boundary SS-B. The upper boundary is defined by the seismic sequence boundary C (Fig. 4.8). SS-B thins in westward direction and is finally truncated by the upper regional unconformity.

Seismic sequence C (SS-C)

The sequence is bounded below by sequence boundary C and seismic sequence boundary D above. The SS-C is lensoidal in shape and is extensively developed and can be traced throughout the Norwegian Channel within the study area. It has aggradational to weak progradational character. The internal character of the sequence is reflection free, but few prograding clinothems can be observed (Fig. 4.8).

Seismic sequence D (SS-D)

Lower boundary is defined by the sequence boundary D. This seismic sequence represents the youngest sequence of the Plio-Pleistocene succession and the seismic facies analysis depicts that this package is mainly composed of ground and lateral moraine ridges and have reflection free internal geometry (Dahlgren et al., 2005). The internal reflection character of this sequence also validates the point that it has been deposited during the same set of the conditions (Fig. 4.8).

4.3 Seismic facies analysis

Seismic facies analysis is a key component of the seismic interpretation workflow because it gives information of depositional processes and environments. The facies and the reflection configuration give information about the stratification patterns, and paleogeography can be inferred from the depositional environments (Mitchum et al., 1977). Facies make up the particular depositional environment, when the sediments are formed (Mitchum et al., 1977). The main parameters on which we can distinguish different facies are frequency, amplitude, continuity and shape of the reflection (Chapter 3).

On the basis of reflection configuration following seismic facies are analyzed on the data set.

4.3.1 Prograding seismic facies

Such types of facies are formed by the gently sloping clinothems, and clinoform geometry may indicate rate of deposition and water depth at the time of the progradation (Mitchum et al., 1977).

- **Sigmoid seismic facies**

Such facies are observed in late Plio - Pleistocene deposits, and it generally has the “S” shaped geometry. Sediments of such kind generally deposit on slope margins (Mitchum et al., 1977). In the study area high amplitude and continuity are observed in such deposits. The high continuity may indicate the same depositional environment, while the high amplitude may be due the high impedance contrast between shale (mud) and sandstone (sand).

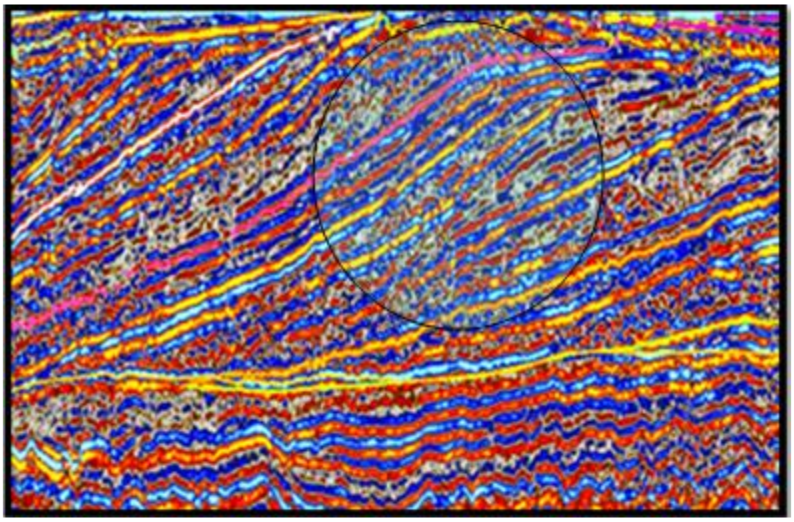

Fig. 4.9: Seismic section generally showing the sigmoidal seismic facies.

- **Oblique sigmoid seismic facies**

This facies is generally formed by alternate sigmoid and oblique progradational geometry (Mitchum et al., 1977). Topsets are preserved because of less erosion. The offlap break generally shows the older shelf edge position, and the offlap break trajectory may be interpreted in terms of rise and/or fall in the sea level. These have been observed in the northern North Sea area and the offlap break trajectory analysis that generally is interpreted as reflecting rise in the sea level during progradation (Catuneanu et al., 2011), as generally described in Chapter 3.

- **Oblique prograding seismic facies**

Oblique prograding reflection facies is generally formed when topsets have been eroded of prograding clinothems that dip steeply. The topset erosion results in the up dip termination of the clinothem sets (Fig. 4.10). In the study area this erosion is interpreted to have been formed from grounding ice sheets, for more details, see discussion in Chapter 5.

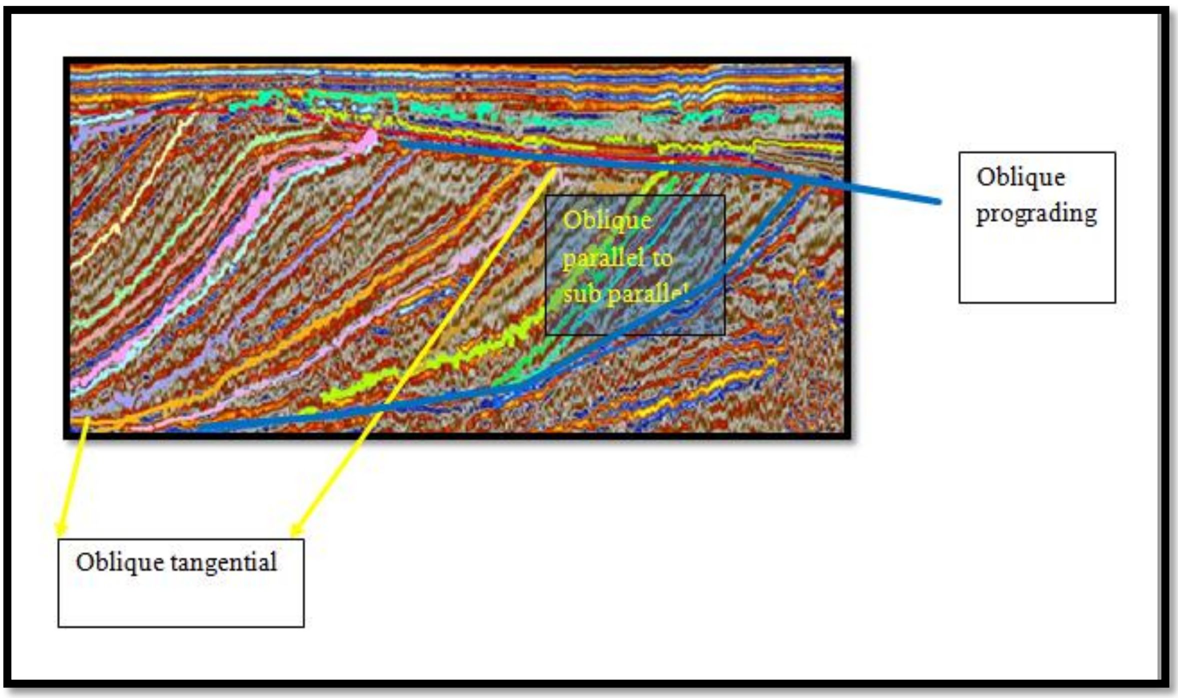

Fig. 4.10: Oblique prograding facies, oblique parallel to subparallel facies and oblique tangential facies.

- **Oblique tangential seismic facies**

This seismic facies is formed by the erosion of topsets of prograding clinothems that generally have gentle dip in the downward direction. The typical geometry results from the concave upward strata that generally have less bottomset dip (Mitchum et al., 1977). Such type of facies have been observed in the in the northern North sea area, and the seismic sequence 7 generally shows this type of geometry (Figs. 4.10 and 4.7).

- **Oblique parallel seismic facies**

Oblique parallel seismic facies is composed of parallel strata dipping at high angle along the downlap surface. This facies geometry can be defined by relatively steep dipping parallel foreset beds truncating down dip at high angle along the downlap surface (Mitchum et al., 1977) (Fig. 4.9). Seismic sequences 2, 3 and 4 generally show this kind of geometry (Figs. 4.10 & 4.7).

- **Shingled seismic facies**

This type of seismic facies generally shows thin prograding seismic pattern, with parallel upper and lower surfaces with thin internal parallel/oblique reflectors. Such type of the facies generally depicts the progradation into very shallow water (Mitchum et al., 1977) (Fig. 4.11).

4.3.2 Divergent seismic facies

Units with divergent facies laterally increase in thickness. This is caused by the thickening of individual subunits within in the main unit. Divergent facies configuration generally predicts the lateral variation in rates of deposition or progressive tilting of the sedimentary surface during deposition (Mitchum et al., 1977) (Fig. 4.11).

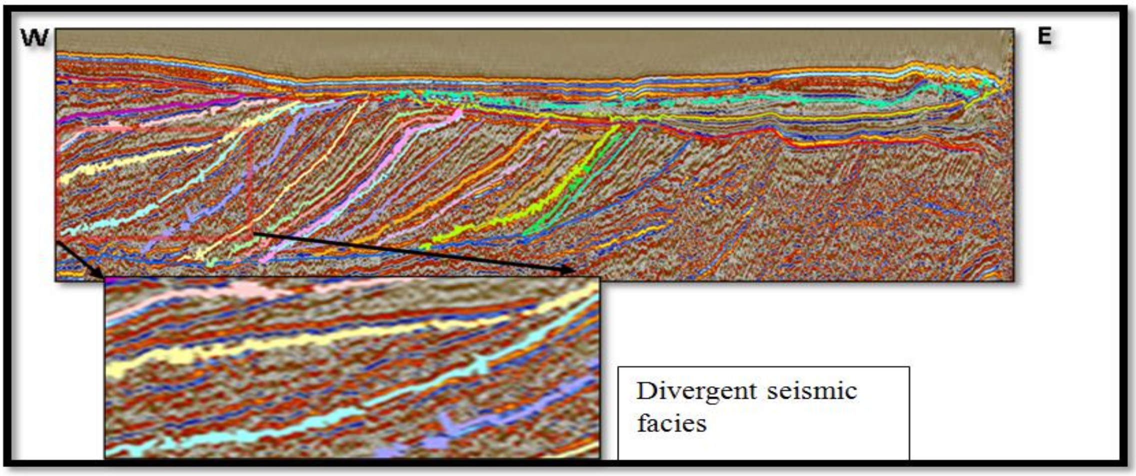

Fig. 4.11: Divergent seismic facies and the polygon showing the zoomed area.

4.3.3 Chaotic seismic facies

This type of seismic facies shows discontinuous and discordant reflections. The internal reflection pattern is unidentifiable and composed of reflectors of various amplitude and frequency. This type of facies is formed by heterogeneous sediments, slump deposits and fluidized sediments. In the North Sea Fan area there are some beds which show chaotic facies deposits. These beds have been interpreted as slide debrites by Nygård et al. (2005), formed by the result of high pore pressure in the interglacial period (Figs. 4.4 & 4.12).

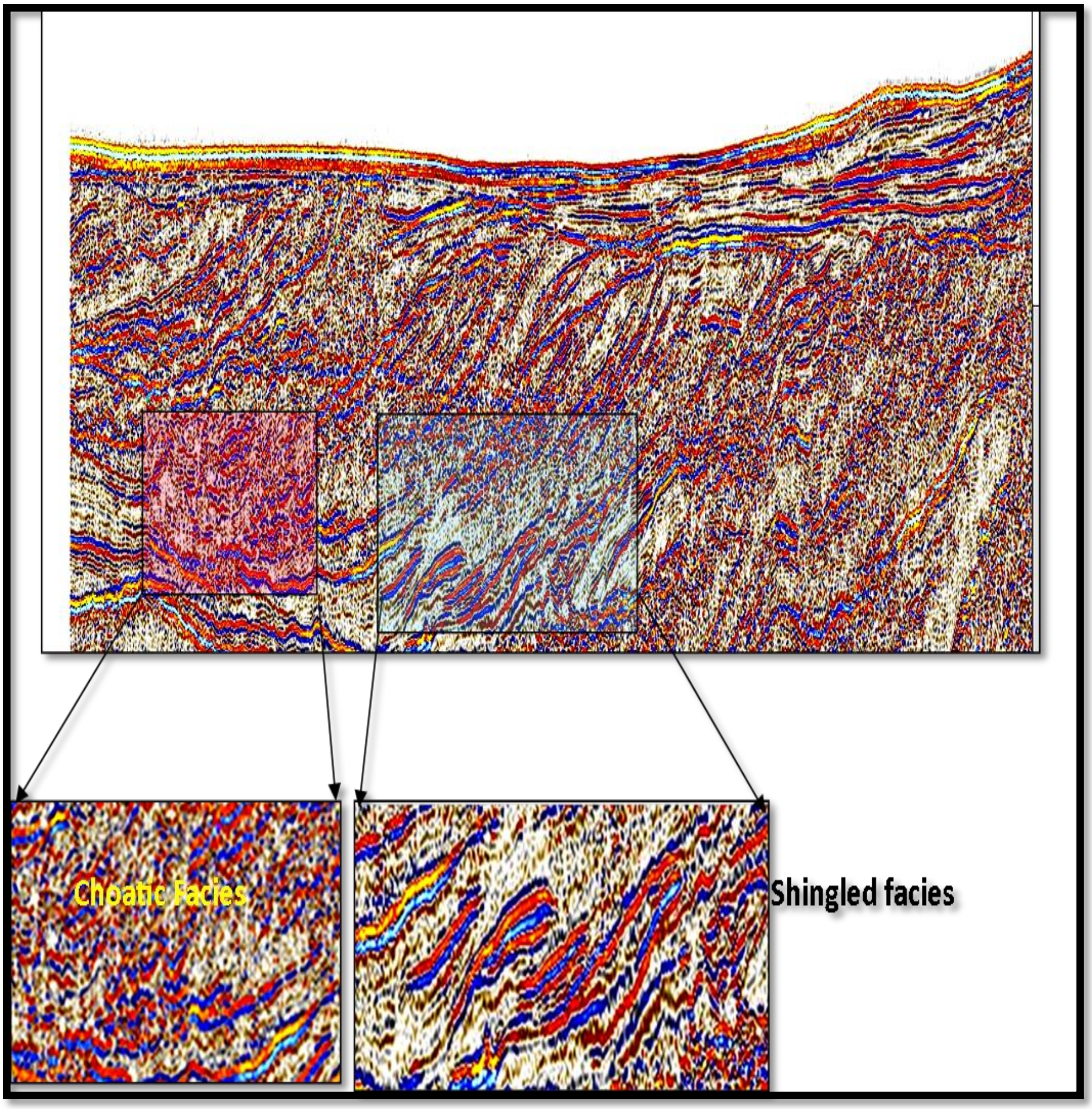

Fig. 4.12: Shingle seismic facies and chaotic (for the location of the line see fig. 4.1 profile GG´).

4.3.4 Channel fill seismic facies

This kind of facies fills the negative relief features such as erosional channels and canyons with sediments onlapping both sides of the channel structure. Such kind of facies describes the structure which is being filled (Mitchum et al., 1977). On seismic line B a channel fill can be observed (Fig. 4.13).

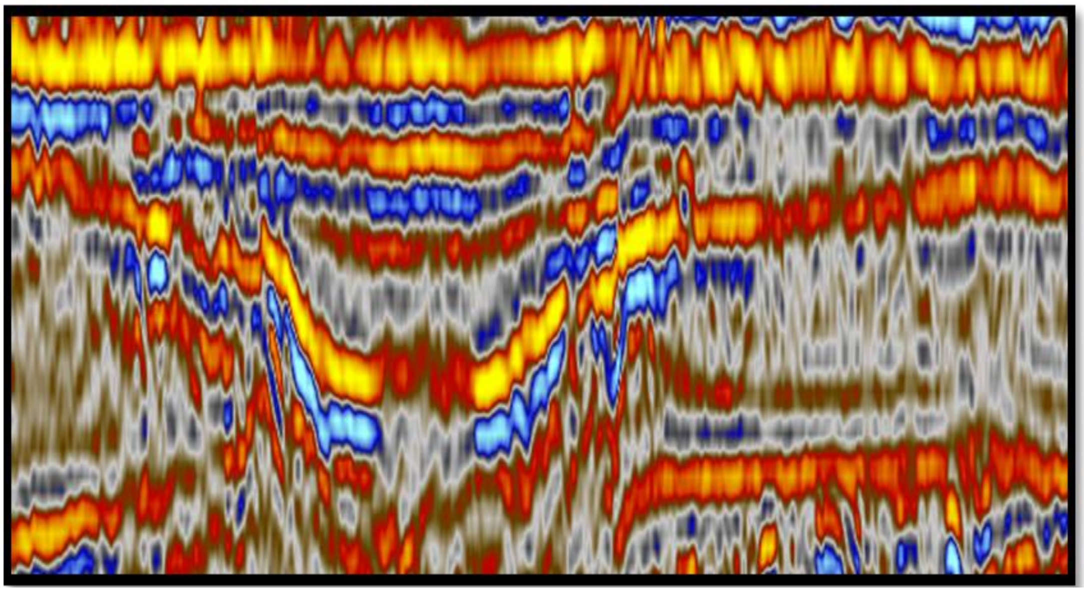

Figure 4.13: Channel fill facies (part of the line CC´, fig. 4.6).

4.3.5 Parallel to sub parallel seismic facies

This seismic facies generally shows consistency in deposition (Mitchum et al., 1977). The seismic sequences B and C generally show this type of deposition (Fig. 4.13).

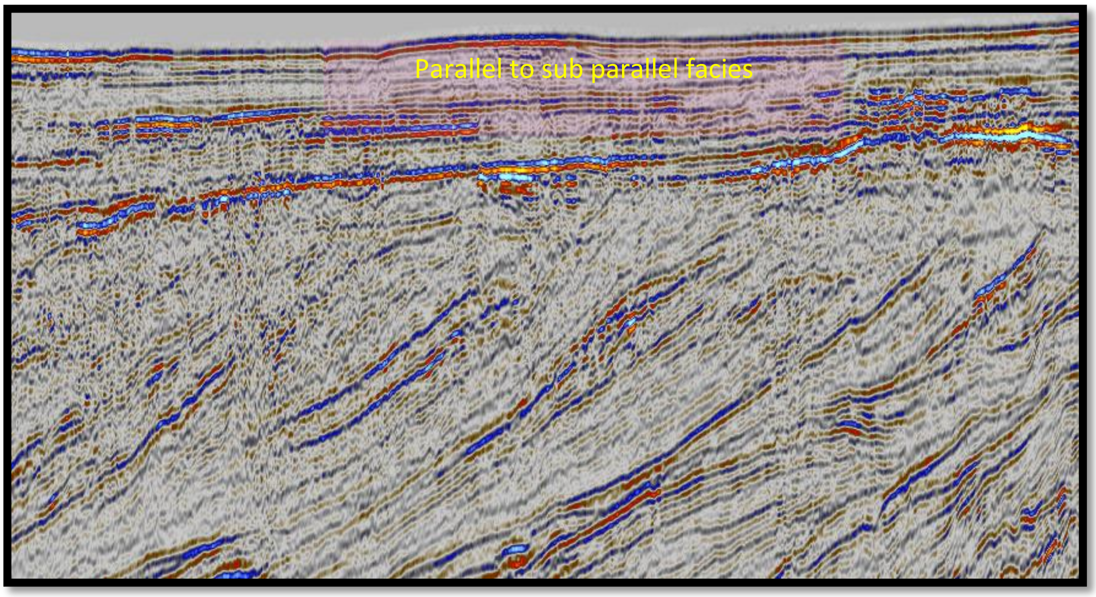

Fig. 4.14: Parallel to sub parallel seismic facies (Part of the line BB´, fig. 4.4).

4.3.6 Staked mounded seismic facies

This facies is a characteristic feature of the North Sea Fan area and generally shows the jointed reflectors that spread out laterally. This facies generally shows medium to low amplitude reflection character and some places displays transparent character. Deposits of this facies are generally formed by gravity flow deposits (Mitchum et al., 1977). In the North Sea Fan area it has resulted from glacigenic debris flow deposits (King et al., 1996; and Nygård et al. 2002) (Fig. 4.15).

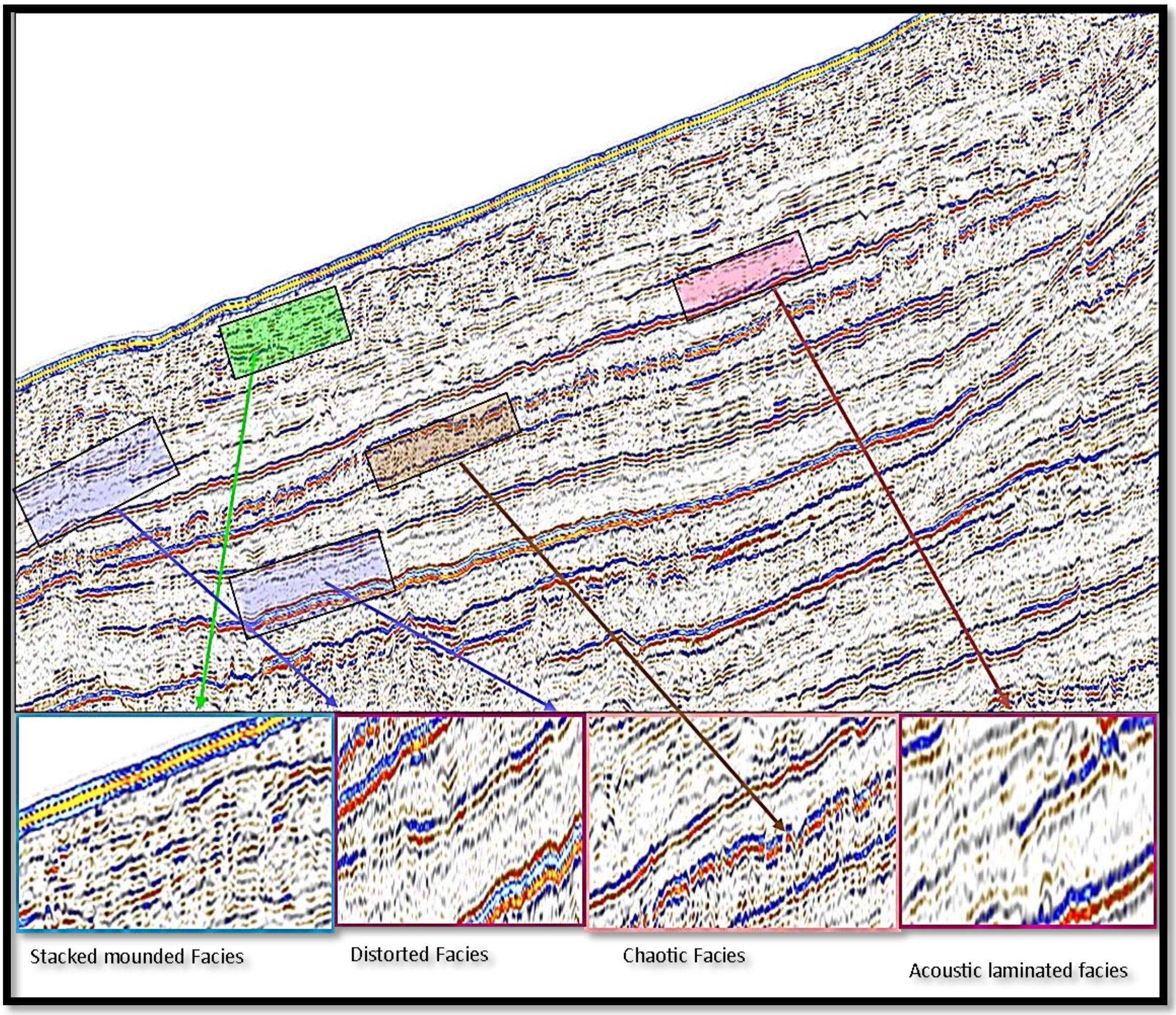

Fig. 4.15: Seismic section showing stacked mounded, distorted, chaotic and acoustic laminated facies. The boxes show areas that are shown enlarged in the figures below the seismic section (Part of the line AA´, fig. 4.3).

4.3.7 Acoustically laminated seismic facies

Such type of seismic facies has been interpreted to represent the peak sedimentation period during deglaciation towards the slow postglacial hemipelagic deposition (Reiche et al., 2011). This facies generally displays the high amplitude reflectors which are separated by low amplitude/transparent facies. The high amplitude may indicate the deposition by debris flows, while low amplitude facies generally indicates the deposition through suspension or by hemipelagic sedimentation. This facies is observed in the North Sea Fan area (Fig. 4.15).

4.3.8 Distorted to transparent seismic facies

This type of facies generally presents deformed low amplitude to acoustic reflection in between high amplitude reflectors. Such facies type indicates the glaciomarine or hemipelagic deposits (Nygård et al., 2005) (Fig. 4.15).

4.4 Time thickness map

Time thickness maps were generated for sedimentary packages along different sequence boundaries. Details of the maps are given below.

4.4.1 Time thickness maps between SS1 and SS15 boundaries

Four thickness maps were generated between the SS1 & SS5, SS5 & SS8, SS 8 & SS 11 and SS 11 & and SS 15 sequence boundaries. The thickness is up to 300 ms approximately, and dominate transport direction is toward west and NW (Fig. 4.16).

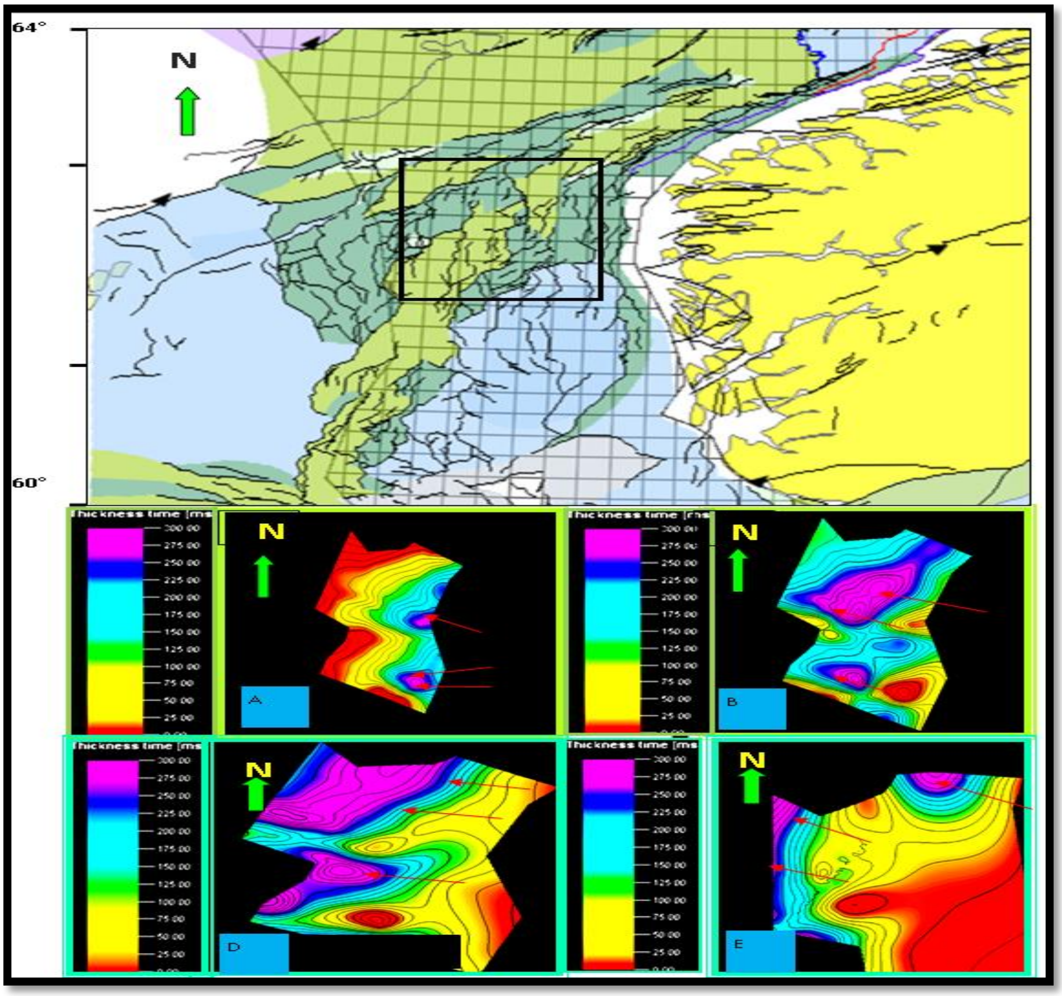

Fig. 4.16: A). Time thickness map between (A) SS1 and SS5 sequence boundaries, B) SS5 and SS8 sequence boundaries 2, C) SS8 and SS11 sequence boundaries D) SS11 and SS15 sequence boundaries. Polygonal frame in the key map shows the position of the time thickness maps.

4.4.2 Time thickness map of megasequence I

The time thickness of megasequence I was generated. The time thickness map of the whole sedimentary package between upper regional unconformity and regional downlap surface generally shows increase in thickness in the NW (Fig. 17)

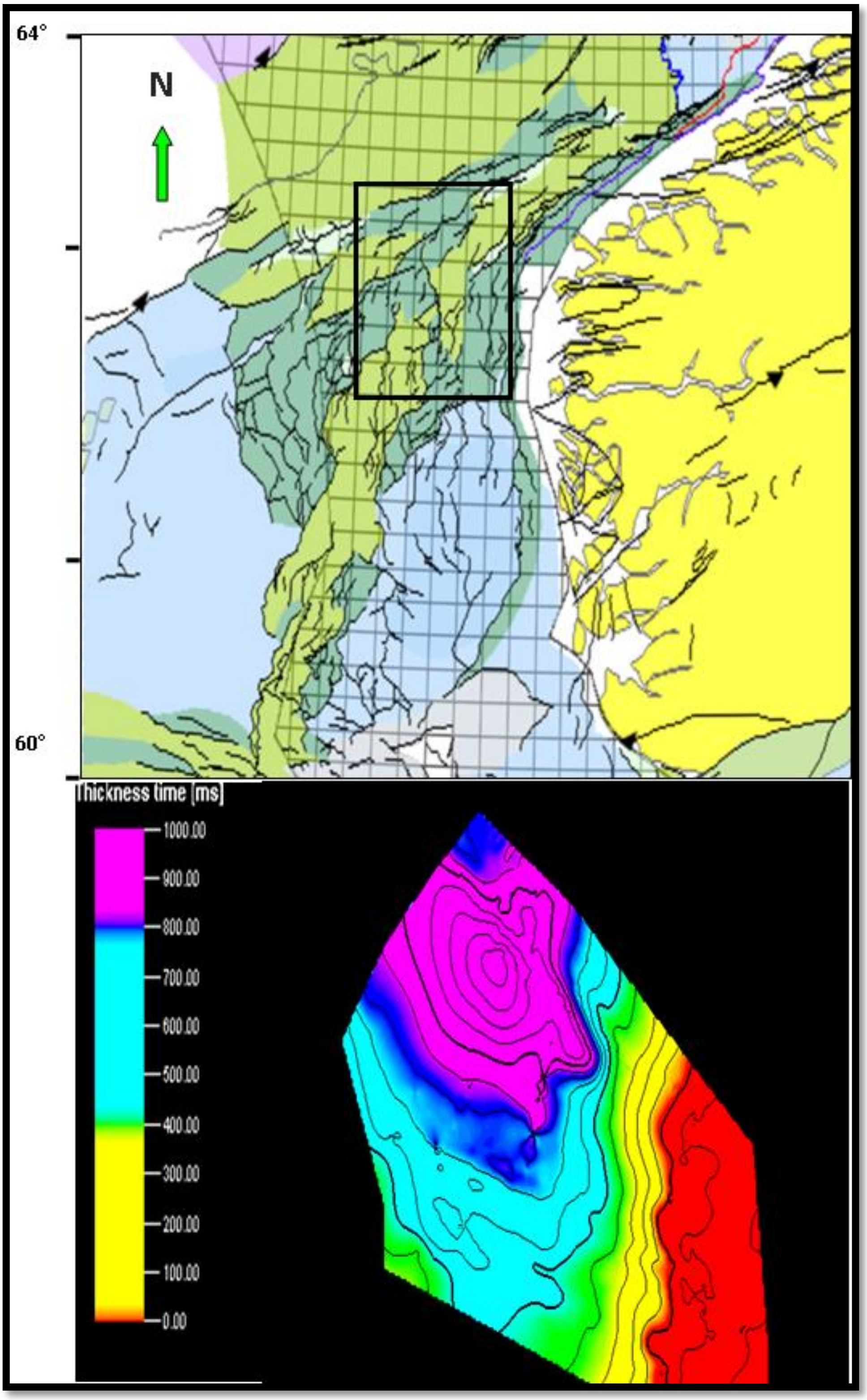

Fig.4.17: Time thickness map of the complete sediment pile between the RDS and the URU. Polygonal area in key map shows the location of the time thickness map.

5. Discussion

A total of 31 sequences along with the four sequences SS-A to SS-D in the Norwegian Channel have been identified and described in Chapter 4. The sequences have been divided into three megasequences, Megasequence I, Megasequence II and the NSF Megasequence, on the basis of depositional environment and geometry. Individual sequences are interpreted mainly to represent glacial-interglacial cycles and the megasequences to particular stages of the late Pliocene to Pleistocene glacial history.

The latest Cenozoic basin infill in the northern North Sea and the mid-Norwegian continental shelf is generally characterized by thick development of prograding clastic wedges (Chapter 2). In the northern North Sea the first large-scale continental ice sheet developed during Plio-Pleistocene time (2.75-2.55 Ma). In mainland Norway deposits of this glaciation has been eroded by glacier ice from the later glaciations. The North Atlantic ice-rafted deposit record (IRD) shows that the first discharge and melting of sediments from debris-loaded ice bergs occurred around 2.7-2.4 Ma (Thierens et al., 2011).

In this chapter ages and regional implications of the 31 recorded seismic sequences will be discussed. Furthermore, the discussion also includes how basin geometry may have controlled sequence development, how accommodation space was created and destroyed, how glacial dynamics and sediment supply influenced upon formation of sequence boundaries, facies and depositional style, and finally the Norwegian Channel and its role in the establishment of the North Sea Fan.

5.1 Age of the sequences

The Plio-Pleistocene Naust Formation in the mid-Norwegian continental shelf was subdivided into five sequences by Rise et al. (2005, 2010), named N, A, U, S and T units from older to younger.

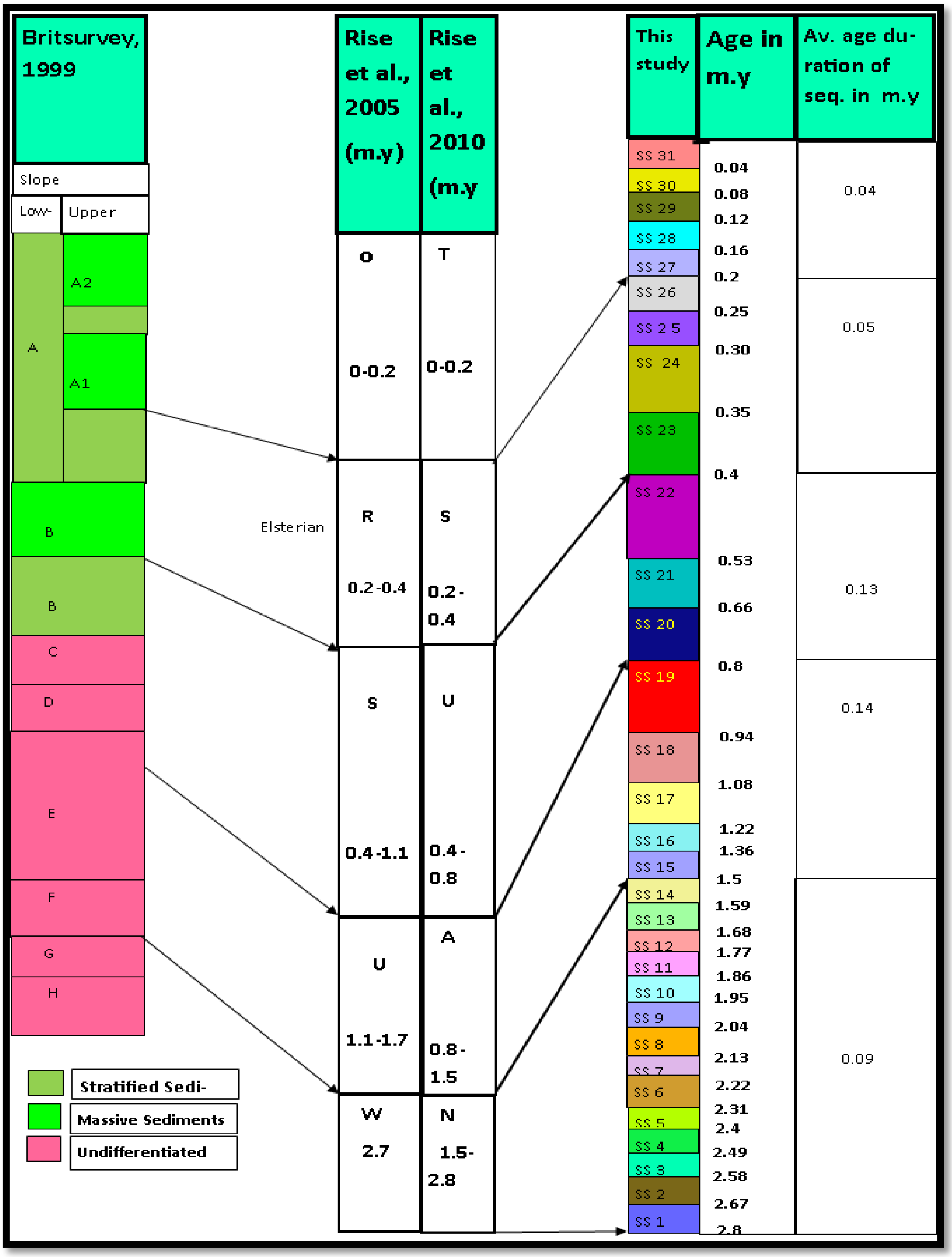

Fig. 5.1: The proposed ages of SS 1 to SS 31 integrated to the Naust units of Britsurvey (1999) and Rise et al. (2005 & 2010).

The stratigraphic scheme of Rise et al. (2010) has been adopted to assign ages to the seismic sequences of the present study. The N, A, and U units in the Naust Formation depict the period from 2.8 Ma to the onset of the third last glaciation (Ottsen et al., 2009). In western

Norway, a similar clastic wedge was formed, and the age of 2.75 Ma has been taken as the maximum age of the upper Pliocene (Dahlgren et al., 2005; Faleide et al., 2002). For the regional downlap surface RDS an age of 2.8 Ma has been assigned by Eidvin et al. (2000), and this age has been applied for the RDS in this study (Fig. 5.1).

With an age of 2.8 m.y. of the RDS, and thus for the whole glacial succession, an average duration for each of the 31 sequences are about 90 000 years (Fig. 5.1). However, by splitting up the 31 sequences by correlations to the N, A, U, S and T units and the chronostratigraphy of Rise et al. (2010), the duration of individual sequences within these units vary between a maximum of 140 000 years in the A unit to a minimum of 40 000 years in the youngest T unit, which should correspond to the Weichselian glaciation. For the sequence SS1 to SS14, here correlated with the N unit of Rise et al. (2010), the average cycle duration is 90 000 years, like the overall average glacial cycle duration calculated for the complete glacial succession with an age of 2.8 m.y.

The variation in glacial cycle duration may have several explanations. The ages given by Rise et al. (2010) have their uncertainties, the correlations (Fig. 5.1) are uncertain, and the character of individual sequences as representing one complete full glacial/interglacial cycle or just a stadial/interstadial of shorter duration is also uncertain. The uppermost sequences SS27-31 may represent stadial/interstadial cycles. A comparison with other parts of the north-eastern Atlantic region may give some indications of how many individual complete glacial cycles that likely can be represented in the study area.

The northern North Sea and the North Sea Fan has a different geological setting than the mid-Norwegian continental shelf (Chapter 2), but, nevertheless, these two areas show similar clastic wedge growth from about 2.74 Ma (Dahlgren et al., 2002, 2005; Hjelstuen et al., 2005; Rise et al., 2005, 2010; Ottesen et al. 2009), as demonstrated above by the correlation between these two areas (Fig. 5.1). The clastic wedges continue into fine-grained deep-water sediments in the Norwegian Sea.

Lee et al. (2012) suggested that the pre-Weicheslian shelf-edge glaciations can be recognized by ice rafted debris (IRD) in the Norwegian-Greenland Sea. The Vøring Plateau holds a long-run glacial history with increases of IRD deposition at 2.74 Ma (Jansen et al., 2000). The first extensive ice advance took place at 1.1 Ma. Until 2.6 to 1.1 Ma the ice sheets were restricted to the fjords and the inner shelf, whereas later ice sheets expanded across the shelf (Hjelstuen et al., 2004). Large ice sheet growth on continents gives rise to increase in ð18O records from calcite in forams from deep sea sediments (Bender et al., 1994) (Fig. 5.2)

Iceland has a good record of glacier deposits (tills and tillites) due to preservation of the glacial sediments by basaltic lava flows during interglacial periods. The composite stratigraphy from east and north of Iceland demonstrates at least 22 glacial-interglacial cycles during the last 3 Ma (Geirsdóttir et al., 2007). Extensive glaciations occurred in Iceland between 2.5 Ma and 0.5 Ma. During the last 0.5 Ma there are five major glaciation peaks.

The data are justifying several major glaciations along with stadial/interstadial periods (Fig.5.2). Generally, there are rather good correlations between the numbers and chronostratigraphic position of the sequences recorded in this study compared with those in Iceland, on the mid-Norwegian continental shelf, and with temperature cyclisity in the oceanic deep-sea water, as reflected by the ð^{18}O record. The recorded glacial/interglacial or/and stadial/interstadial record of the present study, also indicate a change in character of deposition in late Pleistocene, as the shift in character of the ð^{18}O curve (Fig. 5.4).

The deep sea ð^{18}O curve reflects this change about 1 Ma ago (Fig. 5.2), whereas, according to the correlation shown in Figure 5.2, a similar change occurred in the present study area about 1.1 Ma ago.

Additional data on time frequency of the uppermost sequences SS27-SS31 may be obtained from a comparison with variation in ice rafted detritus (IRD) (Mangerud, 2004) (Fig. 5.3). The marine isotope stages 1-6 represent the time interval when the Fennoscandian ice sheet expanded beyond the coast of Norway, as proposed by Lekens et al., (2009). Probably the main growth of the Fennoscandian ice sheet occurred after 42 000 calculated years B.P., as indicated in figure 5.3.

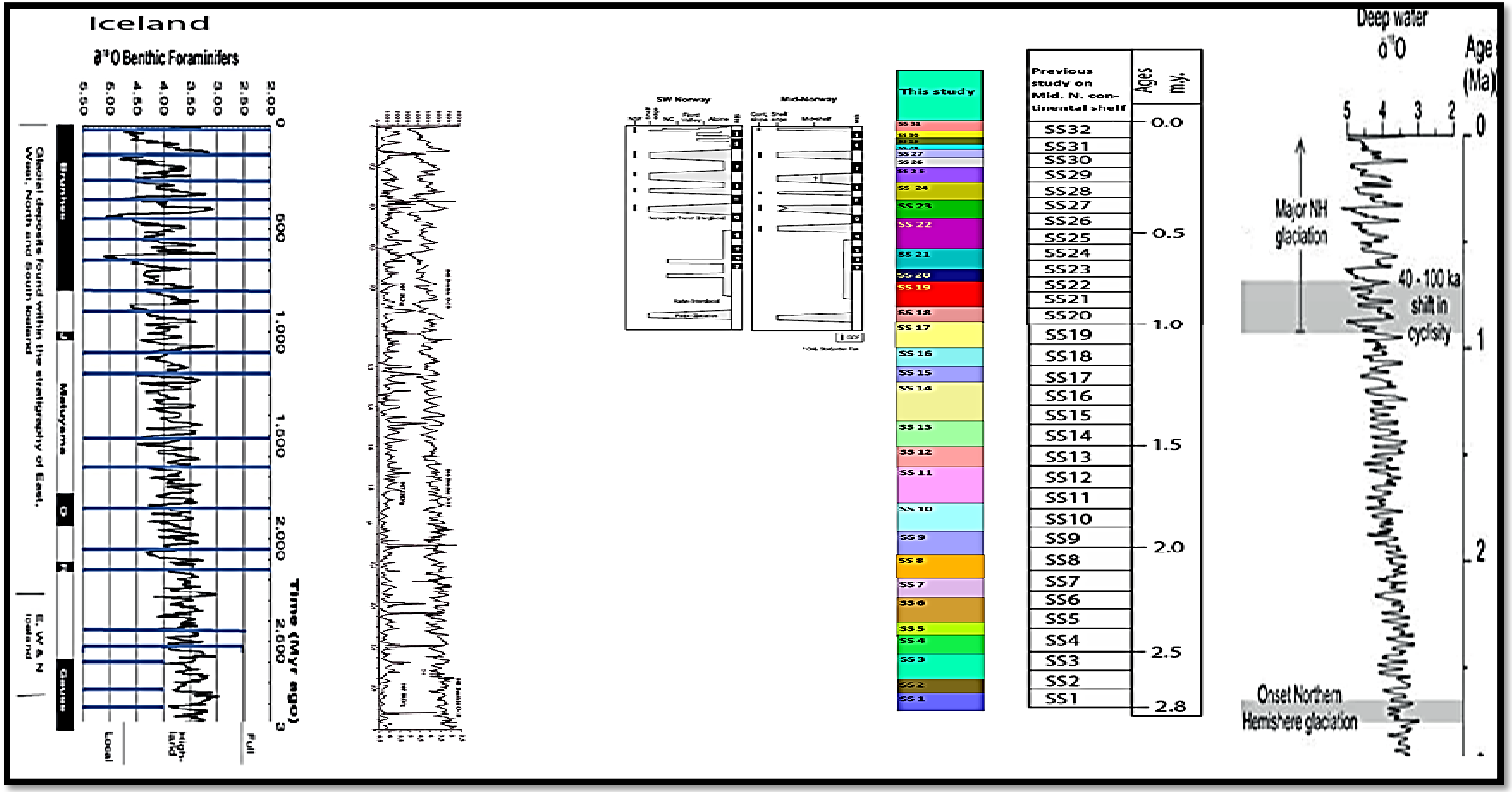

Fig. 5.2: Correlation of seismic sequences of this study with Pleistocene glacial stratigraphy in Iceland (Geirsdóttir et al., 2006), SW Norway and Mid-Norway (Sejrup et al., 2005), and on the mid-Norwegian continental shelf (Hafeez, 2011), together with a comparison with the ð^{18}O and IRD curve (Dahlgren et al., 2005; Jansen et al., 2000).

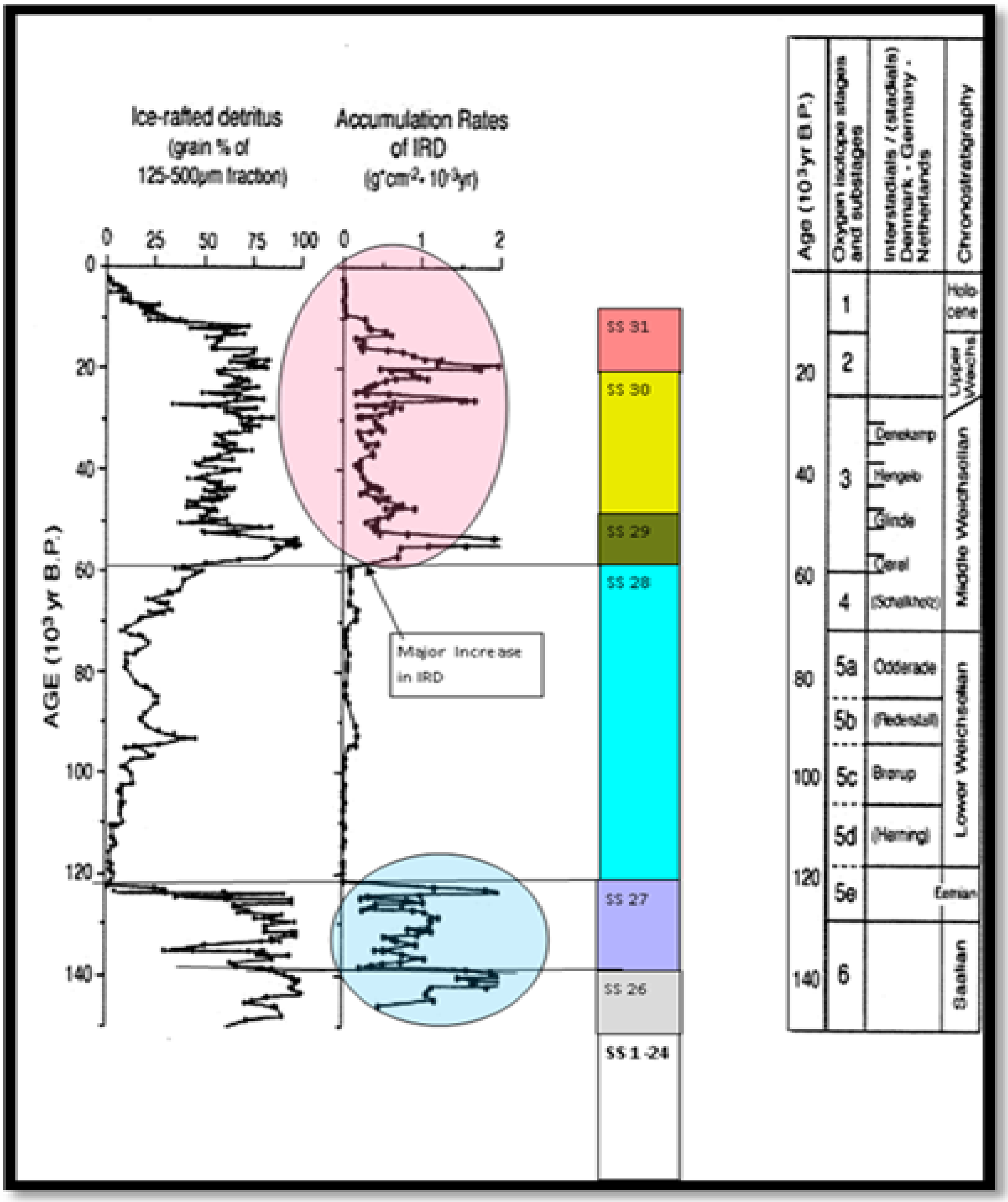

Fig. 5.3: Correlation of the uppermost sequences SS26-SS31 of the present study with variation in ice-rafted detritus (IRD), recorded from the stratigraphic interval of the marine isotope stages 6 to 1 (MIS 6-1) (Mangerud, 2004).

Glacigenic debris flow deposits (GDFs) occurred during the marine isotope stage 6 (MIS6) and were reworked during the Tampen Slide (SS27). Glacial activity increased approximately around 42 cal Ka Bp (Fig. 5.3). The correlation of SS26-SS31 with the IRD curve of Mangerud (2004) suggests that at least some of the uppermost high-frequent seismic sequences represent stadial/interstadial couplets.

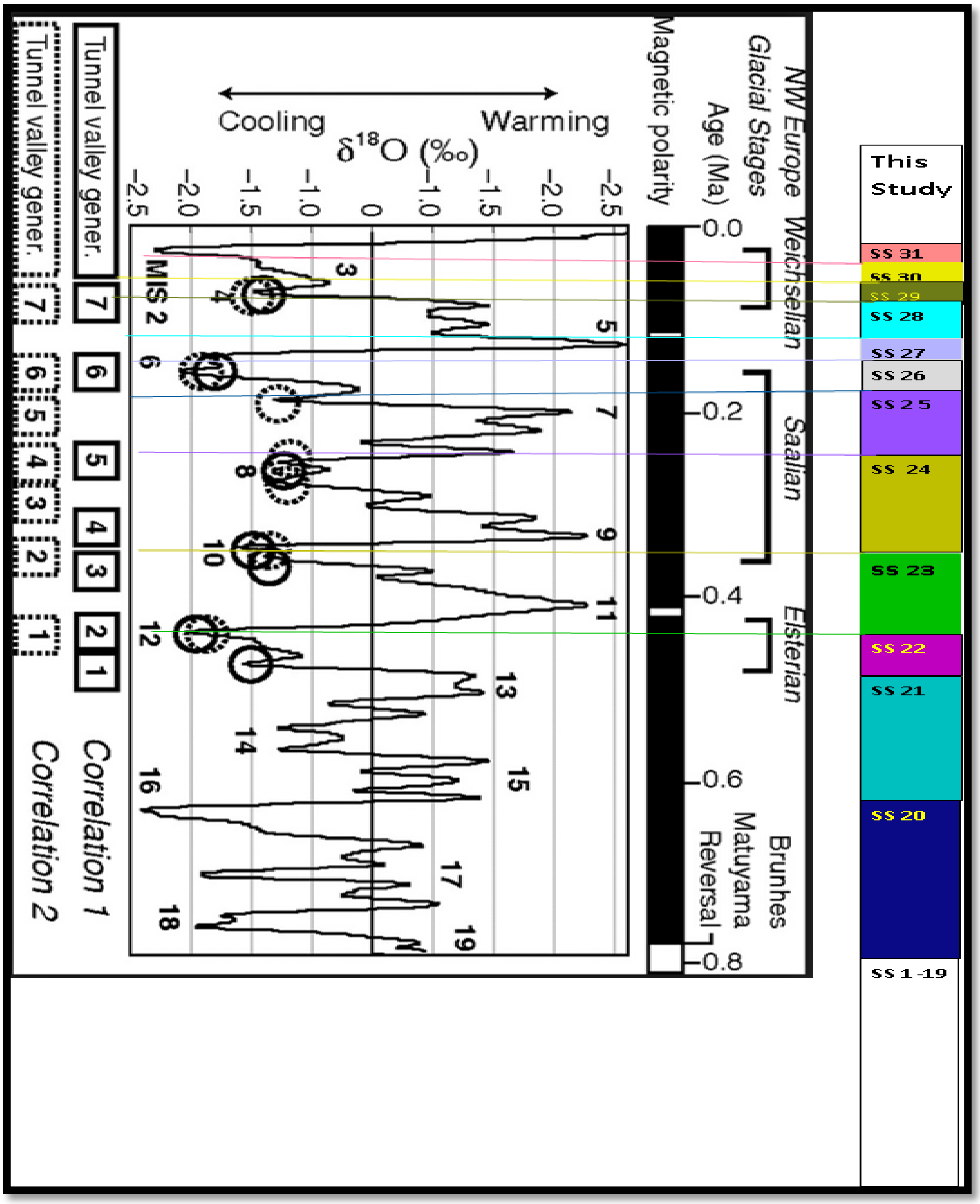

Fig. 5.4: Correlation of the uppermost sequences of the present study with variation of ð^{18}O, recorded from the marine isotope stages 19 to 0 (MIS 19-0) (Stewart & Lonergan, 2011).

5.2. Accommodation space and sediment supply

Accommodation space and sediment supply are critical factors for sedimentation and formation and preservation of stratigraphic sequences (Chapter 3). The accommodation space during Plio-Pliocene sedimentation on the Norwegian continental shelf is attributed to tectonic movements and/or loading induced subsidence, as well as eustatic sea level (Solheim et al., 1996; King, 1996; Lebesbye and Vorren, 1996; Dahlgren et al., 2002 a, b; Hjelstuen et al., 2004b; Sejrup et al. (2004) (see also Chapter 2).

In the study area the shape of prograding clinothems of the sequences 1-15 indicate that these sequences were formed when there was a huge accommodation space available along with high rate of sedimentation. A high rate of sedimentation may suggest that the Pliocene fluvial erosion and transport in mainland Norway was replaced by glacial erosion at the onset of the northern hemisphere glaciations may be combined with tectonic uplift.

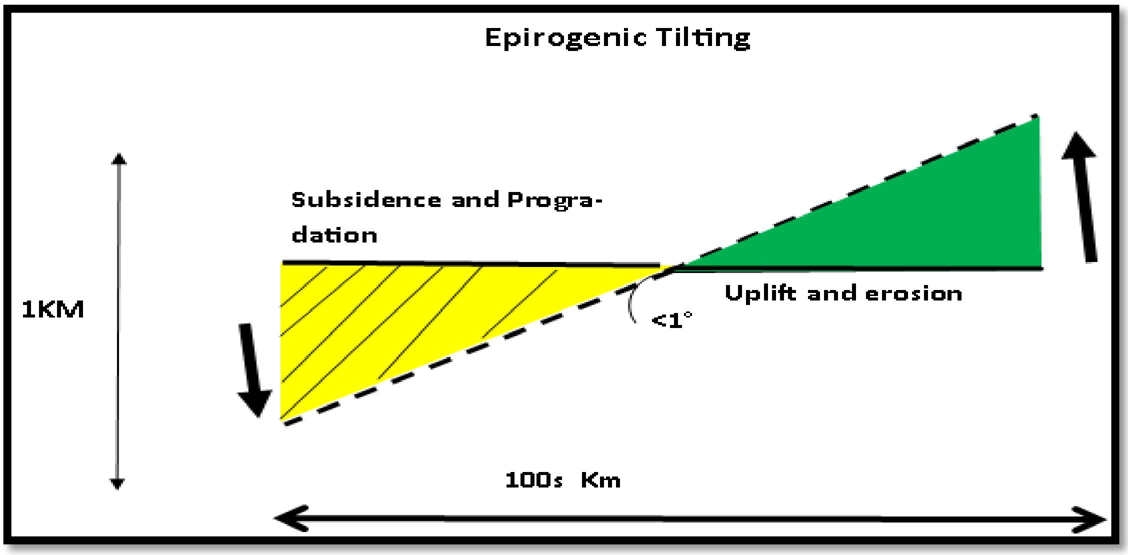

Fig. 5.5: Sedimentary response to epeirogenic tilting (early and later Cenozoic and sagging (Mid-Cenozoic), tilting and coeval uplift and subsidence across hundreds of kilometers, rotation <1° rejuvenated sediment supply and created space for basin-ward progradation (modified after Praeg et al., 2005).

Tectonic uplift and subsidence in the continental shelf area, along with eustatic sea level changes, caused fluctuation of the relative sea level. These relative sea level changes played an important role in the creation and destruction of the accommodation space in the northern North Sea (Jordt et al., 2000). The principle of tectonic uplift in the landward side and concomitant subsidence in the basinward side is shown in (Figure 5.5).

West to north-west prograding Plio-Pleistocene depositions in the northern North Sea area consist of immature, poorly sorted sediments with abundant and granitic rock fragments, suggesting that basement rocks were the main source for the terrigenous material (Anell et al., 2010). By the approach of the Pleistocene ice sheets to the shelf edge, the thickness of the stacked glacial cyclothems is the result of the combination of changing degree of sediment supply, depositional processes, accommodation space and glacial dynamics at the shelf edge margins (Fig. 5.6).

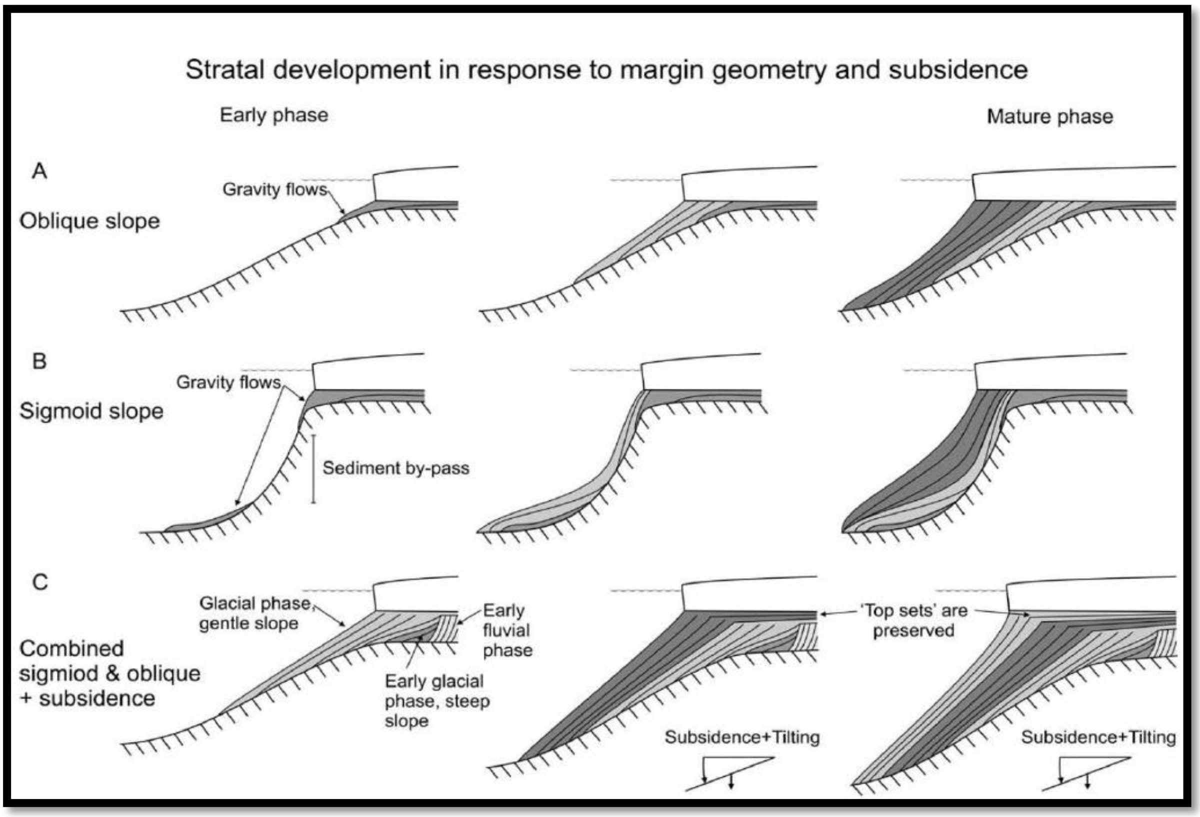

Fig. 5.6: Conceptual model showing the effect of margin geometry and subsidence on the resulting progradation and stratal stacking pattern of prograding clastic wedges in a glacial setting at a shelf edge (Dahlgren et al., 2005).

Sediments are compacted under the load of overlying sediments, water and grounded ice sheets. The lithological contact between previously deposited compacted glacial sediments and overlying poorly compacted mud or clay sediments has the ability to give rise to a seismic reflection with high acoustic impedance contrast.

In this way, some delicate stratal patterns that likely formed at the shelf edge and at ice sheet margins (Fig. 5.6) may be have been seismically reflected. The seismic sequence boundaries SS 3, SS 4, SS 5, SS 6 and SS 7 represent high amplitude seismic surfaces that may reflect high acoustic impedance contrast produced by successions of such types of sediments (Fig. 4.6).

The movements of the glaciers along the shelves of NW Europe were temporary in character (Nygård et al., 2004; Dahlgren et al., 2005). The subsidence has been considered to have varied between 0.1 and 0.2 m/ka (Solheim et al., 1996; King, 1996; Lebesbye and Vorren, 1996; Hjelstuen et al., 2004; Dahlgren et al., 2005).

5.3 Shelf edge trajectory analysis

Shelf edge trajectories present indiation about variation in the ratio between creation of accommodation space *versus* rate of sedimentation (A/S), and hence the glacial dynamics as function of changes in relative sea level. There are three primary classes of shelf edge trajectories (Bullimore et al., 2005), positive shelf edge trajectories, negative offlap trajectories and flat or zero (Chapter 3).

5.3.1 Positive shelf edge trajectory

Positive shelf edge/offlap break trajectories generally show progradation during rising relative sea-level and the topsets may be preserved.

The positive offlap break trajectory indicates that there were high rates of sediment supply and creation of accommodation. The steeper angle of offlap break trajectory indicates high sediment supply and accommodation space creation during the deposition (Fig. 5.7). In the study area the seismic sequences 11, 12, 14, 16 and 17 show positive (ascending) offlap break trajectories, that probably could be due to the rise in sea level during their deposition (Figs. 4.6 and 4 .7).

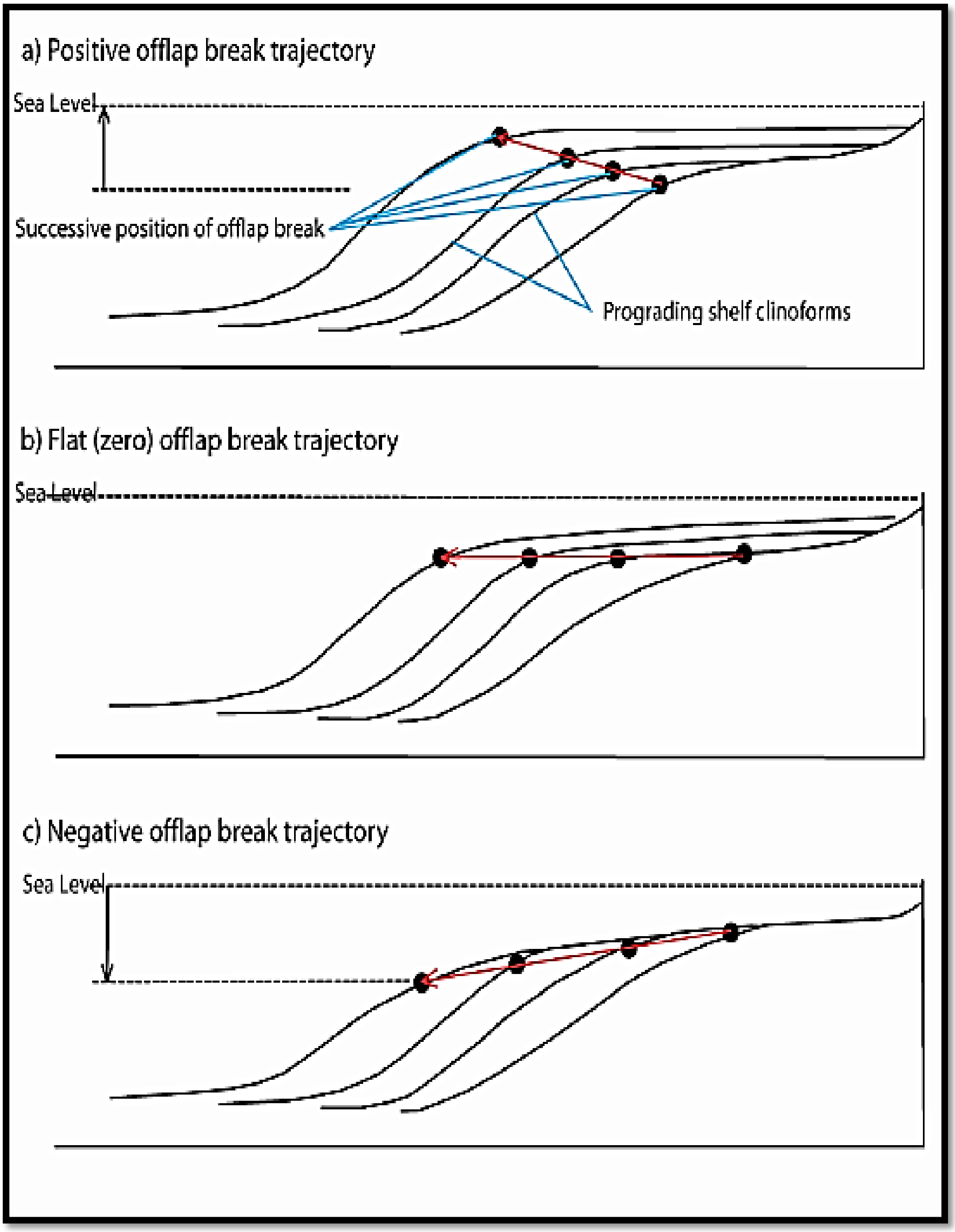

Fig. 5.7: Different scaled prograding shoreface and prograding shelf clinothems. A) Positive offlap break trajectory. B) Flat or zero offlapbreak trajectory. C) Positive offlap break trajectory (Bullimore et al., 2005).

5.3.2 Negative shelf edge trajectory

Negative shelf edge trajectories generally indicate sediment progradation during falling or/and subsequent early rise of relative sea-level (Fig. 5.7). During that period the rate of sediment supply is low, and creation of accommodation space is negative. In this case actually no accommodation space is being created but progradation is generally the result from high rates of sediment supply. It generally represents a forced regressive-falling stage systems tract or a lowstand wedge systems tract (Helland-Hansen and Gjelberg 1994; Bullimore et al., 2005; Van Wagoner et al., 1988; Posamentier & Vail 1988; Posamentier et al., 1988). Negative offlap break trajectories were observed in SS 15 and SS 18 in line CC´ and FF´ (Figs. 4.6 and 4.7).

5.3.3 Flat (zero) shelf edge trajectory

Flat (zero) shelf edge (offlap break) trajectory generally represents low and equal rates of sediment supply and creation of accommodation space, resulting in flat or zero offlap break (and shelf edge trajectory) (Fig. 5.7). Flat offlap break trajectories are generally found in gently prograding to aggrading systems tracts.

5.4. Glacier dynamics and ice flow model

The movement of a glacier is critical and mainly depends upon temperature and gravity (Benn & Evans., 2010). Temperature conditions at the base of a glacier are particularly important. A warm or wet base glacier has more erosional effect and movement than a cold base glacier. This is also valid for large continental ice sheets (see also Chapter 3).

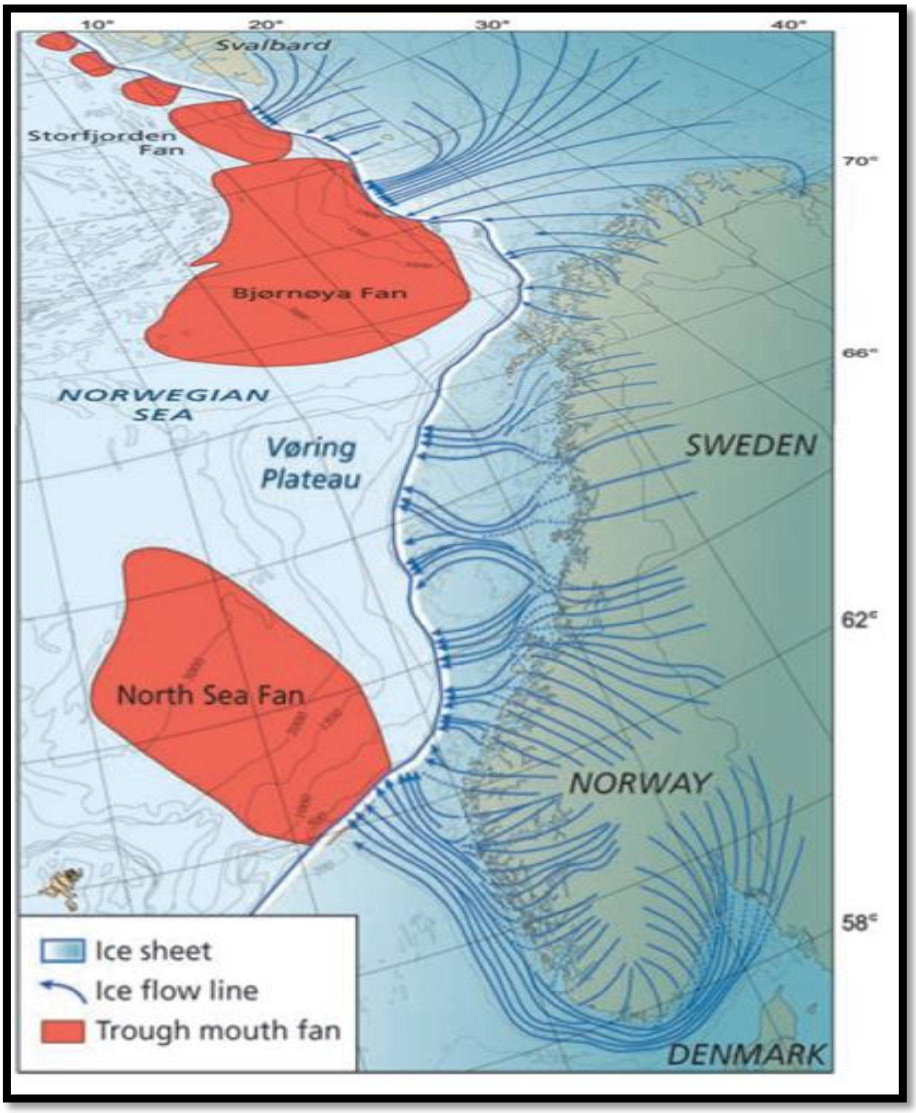

Fig. 5.8: Inferred ice flow pattern, location and extent of trough mouth fans during large ice ages on the Norwegian continental margin, modified after Vorren and Mangerud (2006); from Wohlfarth et al., 2008.

In the present study area the deposition has been made by both valley glaciers, Norwegian channel ice streams, and by laterally extended ice sheets. Mega-scale lineations are found along the Norwegian Channel and represent the ice flow direction (Ottesen et al., 2005) (Fig. 5.8). These glacial dynamic processes have generated a pronounced erosional boundary in the study area, the upper regional unconformity (URU). The topsets of sequences SS1 to SS8 are truncated along this boundary, as shown in Figures 4.6 and 4.7. An overall and general model of the glaciomarine depositional environments and its erosive and depositional elements is shown in Figure 5.9.

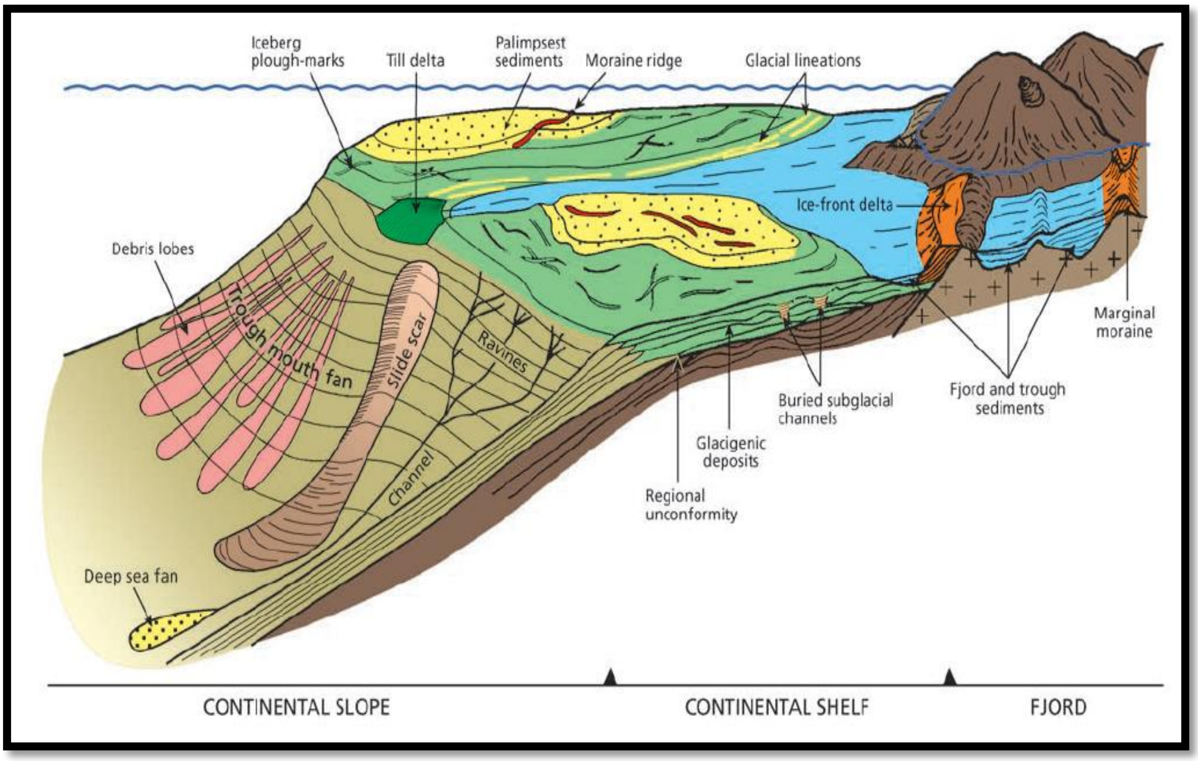

Fig. 5.9: Schematic model of the main glacigenic morphological elements and lithofacies of the Norwegian continental margin, modified after Vorren and Mangerud (2006); from Wohlfarth et al., 2008.

5.5 Origin of megasequences

The megasequences are inferred to represent three major stages in the glacigenic development of the present area of the Norwegian continental shelf. Their origin is discussed below.

5.5.1 Megasequence I

Megasequence 1 is confined at the base by the RDS (regional downlap surface) and at the top by the URU (upper regional unconformity) (Chapter 4). The overall progradational pattern of the megasequence is interpreted to be the result of deep glacial erosion in mainland Norway and glacial transport towards the shelf edge, beyond which there was a high accommodation space allowing the glacial sequences SS1-SS18 (Chapter 4). The basin might have been deeper than 500 m (Faleide et al., 2002).

Local erosional boundaries in megasequence I, such as the sequence boundary 16 (Fig.4.6), could have been preserved subsequent to increased subsidence, as suggested by Anell et al. (2010). The change in depositional geometry from high progradational to low progradational pattern after sequence boundary 16, as recorded in the sequences 16 and 17 (Chapter 4, Fig. 4.6), may be due to rise in sea level and a more landward directed shift in deposition of the sequences.

Sequence boundary 19 indicates a fall in relative sea level during deposition of SS19. Some erosional features along the sequence boundary may also imply sea level fall and erosion from ice or submarine (Fig. 4.6). High dip angles in seaward direction of several prograding clinothems, from SS1 to SS15 (Fig. 4.6), might have been caused when the glacial margin was located at the shelf edge for a longer time, allowing huge amounts of glacial debris to be deposited close to the shelf edge, as in the mature phases in formation of clastic wedges and clinothems (Figs. 5.6 and 5.9).

The foresets of the prograding glacial clinothems represent shelf growth in front of grounding lines (Fig. 5.6). The truncation of the sequences SS1 to SS15 by the URU (except SS10, SS11 and SS12 that have offlap breaks preserved) are inferred to be the result of repeated advances and erosion beneath successive grounded ice sheets, thus creating the URU as a composite unconformity, as suggested by Dahlgren et al. (2005) (Figs. 4.6, 4.7). Preserved offlap breaks may indicate less erosion, or that the ice sheet was at its buoyancy limit, at this point; offlap break trajectories showing ascending trend indicate sea level rise, as demonstrated by SS 16, 17 and 18 (Figs. 4.6 and 5.7). Major depocenter was located in the NW direction as can be seen in figure 4.17.

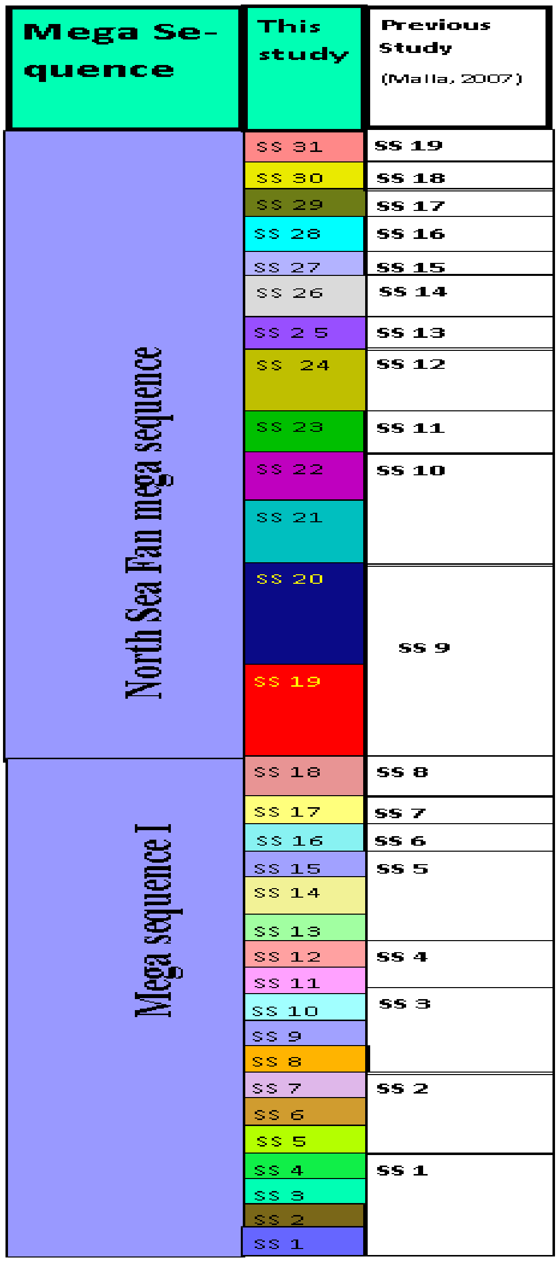

Fig. 5.10: Seismic sequences observed in this study along with the previously study (Malla, 2007).

5.5.2 Mega sequence II

The megasequence II consists of more or less flat lying units that were deposited in the Norwegian Channel during several glacial maxima. The megasequence is organised in four aggradational to slightly progradational seismic sequences (Fig. 4.8 and Chapter 4 for further description).

Erosional channels along the lower boundary SS-C may have been formed as melt water channels (Fig. 4.8) when the ice sheet retreated from the shelf edge during a warmer period. The smooth SS-B boundary is may be formed beneath a floating ice sheet. According to Sejrup et al. (1995), fast flowing, floating ice streams had the ability to deposit till without scouring underlying sediments, thus giving rise to the aggradational geometry. The undulating morphology of the lower boundary of SS-A (Fig. 4.8) may indicate that the ice sheet of this stage again was grounded.

5.5.3 North Sea Fan Complex

The North Sea Fan Complex was formed by the deposition from fast flowing ice streams along the Norwegian Channel (King et al., 1995). The most important facies in the fan complex, glaciogenic debris flow deposits (GDFs) and glaciomarine sediments, reflect in their internal stratigraphy and depositional architecture many glacial and interglacial cycles with little hemipelagic material (Sejrup et al., 2005; Nygård et al., 2005; Lee et al., 2012).

The strucureless facies of SS23 and SS27 (Figs. 4.3 and 5.11) indicate deposition as debris flow deposits subsequent to slope failure. Large volumes of mud material was likely introduced to the upper fan slope due to melting of the grounding ice sheet which caused the slope failure (Nygård et al. 2005). The transparent seismic sequence SS 24 may have been formed in a similar way, by gravity flows or glaciomarine processes; the undulating shape of sequence boundary 24 may reflect the slide hollow of the Møre Slide. A glaciomarine depositional environment is supported by the presence of some laminated beds (Nygård et al., 2005).

King et al. 1996	Nygård et al. 2005	Gen. Inter-pretation	This Study
Seq. 1-4	P1a-d	GDF	SS 29 to SS 31
Seq. 5	P2	G.M?	SS 28
Seq. 6 TS	P3 TS	Debrites	SS 27
Seq. 6	P4a-c	Mainly GDFs	SS 26
Seq. 7	P5	GDFs	SS 25
Seq. 8	P6	Gravity Flow	SS 24
Seq. 9 MS	P7 MS	Debrites	SS 23
Seq. 9	P8	Mainly GDFs	SS 21 and SS 22
Seq. 10 /11	P9 Sc	Debrites	SS 19 and SS 20
	P10	GDFs	

Fig. 5.11: Correlation of North Sea Fan sequences observed in this study with the previous work. GDFs=Glacigenic debris flow, G.M= Glaciomarine (modified from Nygård et al., 2005).

The stacked mounded facies of SS29 to SS31 may indicate the deposition by grounding shelf edge ice sheet; debris flow transport is only possible when the grounding ice sheet is present very close to the shelf edge. As suggested by Lee et al. (2012), debris flows were generated from till deltas/grounding zone wedges deposited by ice streams at the shelf break (Fig. 5.9). SS25 (P 5) and SS26 (P4) represent glacigenic debris flow deposits that formed when the ice was present at the shelf edge (Fig. 4.4).

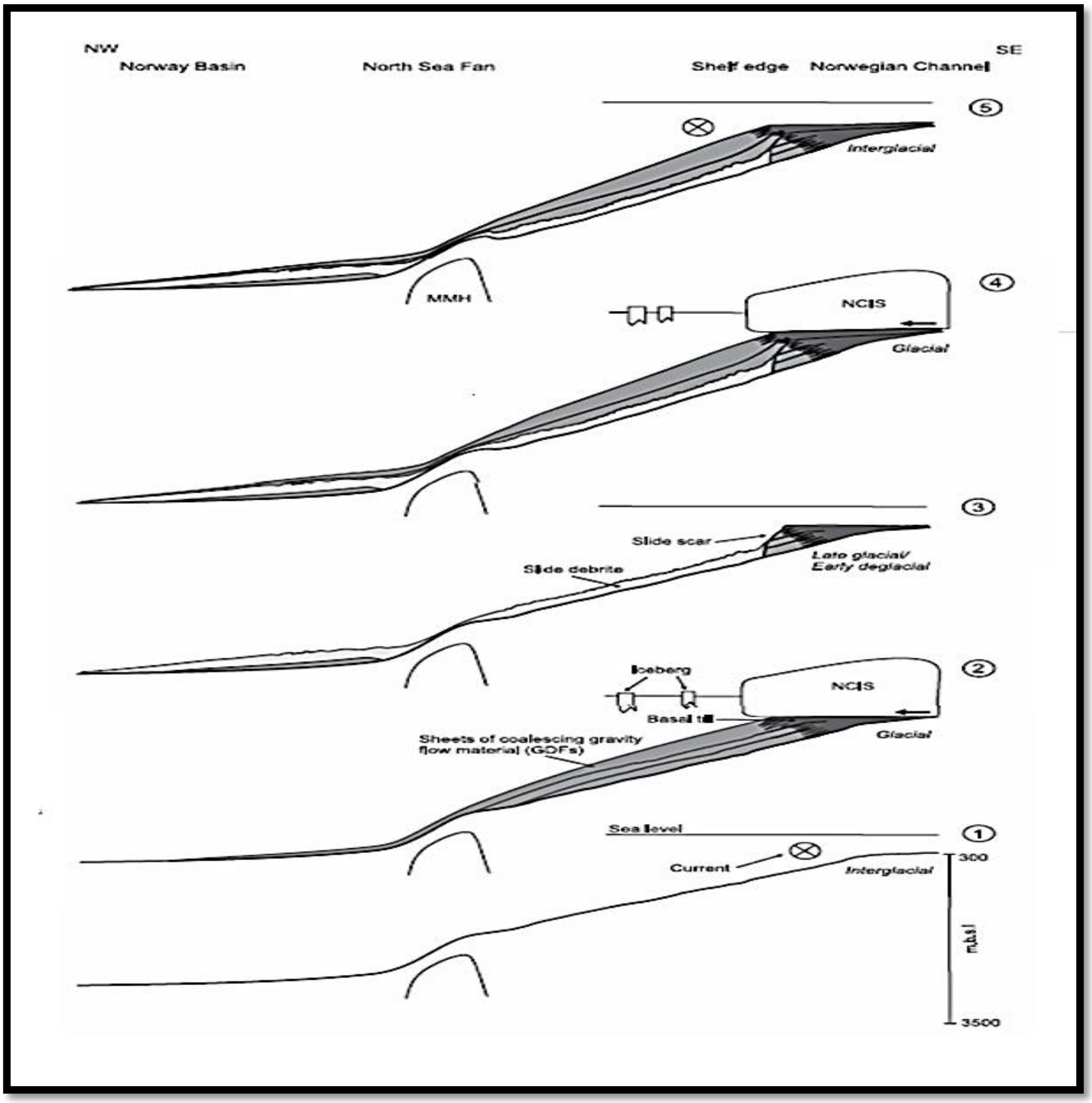

Fig. 5.12: Conceptual models for the geological development of the North Sea Fan, during one single glacial–interglacial cycle. m.b.s.l.: meters below sea level; MMH: Møre Marginal High; NCIS: Norwegian Channel Ice Stream. (Sejrup et al., 2004).

The presence of ice margin moraines indicates that ice sheets were grounded at the shelf edge for rather long time and dumped sediments at the grounding line (Fig. 4.4). Many processes may explain sediment deposition at a grounding line of an ice sheet, as that at the edge of the North Sea Fan. Most relevant processes are subglacial melt-out and lodgment, and dumping of supraglacial debris during iceberg calving (Powell, 1991).

Sediments being deposited at the grounding line may in some cases be stabilized, but very often they get redeposited, as illustrated in the conceptual models of Vorren and Mangrud

(2006) and Sejrup et al. (2004) (Figs. 5.9 and 5.12, respectively). This may be the reason why the shelf slope of the North Sea Fan consists of a series of slide scars (cf. Fig. 5.9) with steep head walls which give impression like syn-sedimentary faults (Bryn et al., 2005). These slide scars may be filled with glaciomarine or debris flow deposits, occasionally it may trap laminated contourite sediments due to influence of oceanic currents during interglacial time (King et al., 1996), as interpreted to be present in SS21 and SS22 (Fig. 4.4).

5.6 Correlation between the Norwegian Channel and North sea Fan

The results presented in this study (Chapter 4) substantiate the hypothesis that glacial sediments were deposited onto the North Sea Fan at the mouth of the Norwegian Channel during phases of shelf-edge glaciation and were subsequently reworked downslope by gravitational processes (King et al., 1998). The Troll bore core stratigraphy (Chapter 2), including two pre-Weichselian glacigenic sediment packages, the lower of which comprising the till unit L6, constrained to ca. 1.1 Ma (Chapter 3) (Sejrup et al., 1995), represents some sort of correlation between till units deposited in Norwegian Channel and those deposited in North Sea Fan (King et al., 1996, 1998; Nygård et al., 2005) (Fig. 5.12).

Sejrup et al. (1995) proposed that the stratigraphical record of the Troll borehole represents only a small portion of glacial events and thus is difficult for correlation. However, in this study a correlation is suggested (Fig. 5.13), by the help of previous studies, between the seismic sequences in the Troll borehole to seismic sequences in the North Sea Fan (see Chapter 4 and figs. 4.4, 4.5 and 4.8).

It should be emphasized that it is not easy to correlate the Troll bore sequences with the stratigraphy in the North Sea Fan because of all sliding and erosion. This restricts the possibility of quantifying how many prograding sequences below URU, at the outer part of the Norwegian Channel, are of Pleistocene age, and how much pre-URU Pleistocene sedimentation occurred in the fan (King et al., 1996).

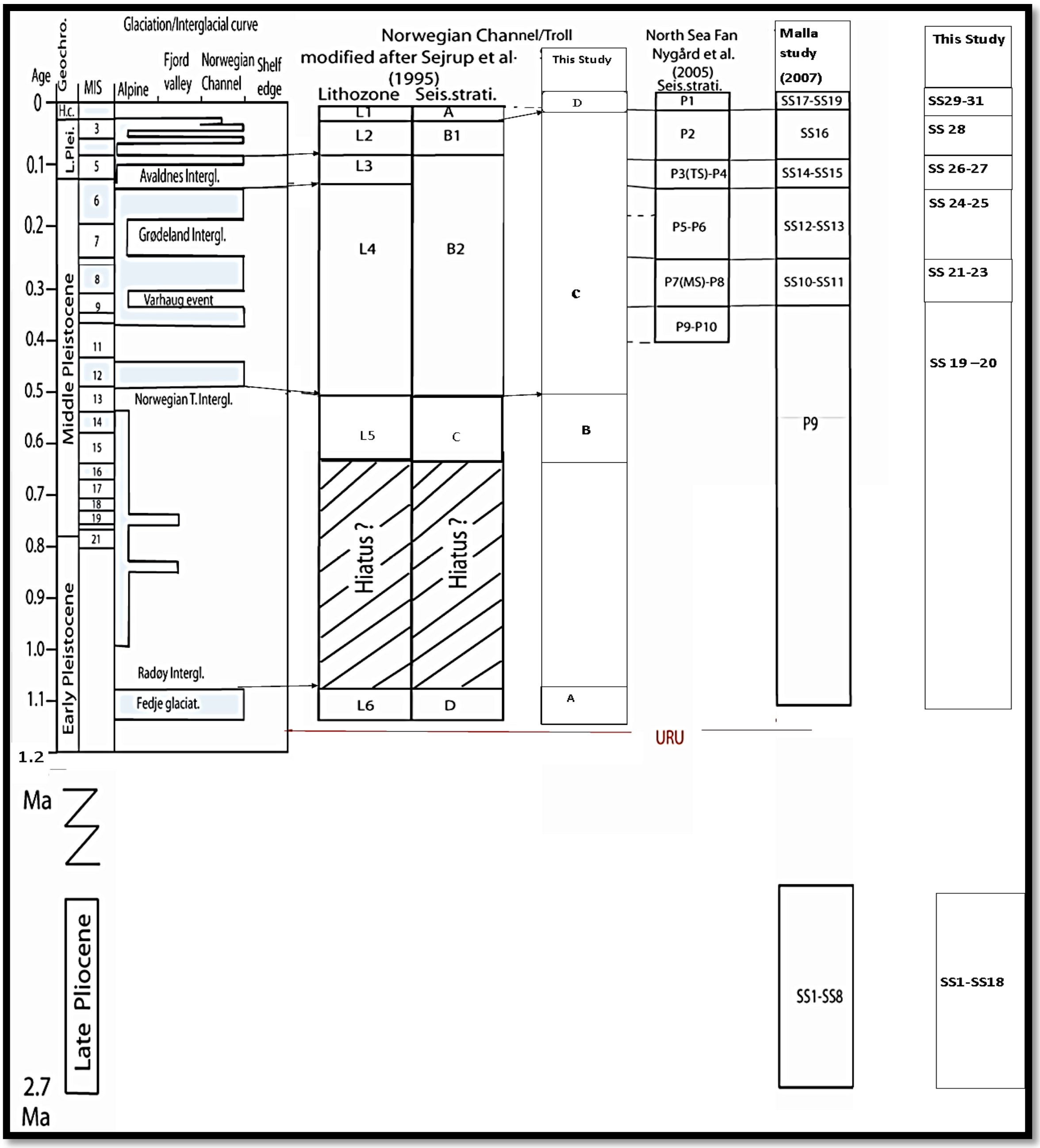

Fig. 5.13: General correlation of sequences observed in the North Sea Fan with the Norwegian Channel stratigraphy (Troll bore hole) and with the stratigraphy of the previous study of Malla (2007).

The Tampen Slide, which is the latest major fan slide event, is also difficult to tie seismic stratigraphically to the channel tills and glacigenic debris flows. King et al. (1996) explained that this is because the cross-cutting relationship at the top of the headwall are not fully resolved and because of the possibility of later, retrogressive failure. Detailed observation of many tie lines gives some indication that the Tampen Slide headwall can have cut the till unit of sequence SS-C in the outer part of the Norwegian Channel.

The till unit of MIS 6 from Fjøsanger, Bergen has been correlated with litho-unit L4 of the Troll borehole (Sejrup et al., 1995), further help to argue that the Tampen Slide was sourced from sequence SS-C. Seismic stratigraphic sequences SS28-SS31 present above the Tampen Slide are also difficult to correlate the outer channel sequences because of Tampen head wall and that the thin sequences at the uppermost part of the profiles are difficult to resolve. If the outer shelf sub-units of seismic sequence SS-C correspond to the Tampen Slide, then the sequences above it can be correlated with the sequence SS-D. The seismic stratigraphic sequence SS-D represents three to four Weichselian glaciation events as suggested by Sejrup et al., (1995) and Lee et al., (2012), there is probability that the seismic sequences SS-28 to SS-31 have been formed during each glacial advance (Figs. 5.13, 4.4).

6. Conclusion

- The Plio-Pleistocene succession of the northern North Sea and adjacent part of the southeastern Norwegian Sea, including the North Sea Fan and the northern part of the Norwegian Channel, developed during 31 recorded events of glacial-interglacial or/and stadial/interstadial cycles, represented by 31 seismic stratigraphic sequences (SS1-31). The 31 glacial events correspond roughly to numbers of glacial cycles reported from the mid-Norwegian continental shelf, in deep-sea sediments and from Iceland.
- The 31 sequences are distributed in three major glacigenic units of different depositional setting and architectural style: megasequence I, North Sea Fan (NSF) megasequence and megasequence II.
- Megasequence I consists of SS1-18 and developed by deposition of till, debris flow sediments and hemipelagic mud from ice sheet margins at the shelf edge in the up to several hundred meters deep basin, during successive progradations of cyclothems, each representing one glaciation. The sequences downlap onto a regional downlap surface (RDS) at the bottom of the glacigenic Pleistocene succession and are upwards truncated by an upper regional unconformity (URU), formed as a polygenic erosional surface during repeated advances of grounded ice sheets.

- Megasequence II was formed after a significant change in basin configuration and depositional style from progradational to aggradational on top of the URU. Megasequence II contains sequences SS-A to SS-D and occurs in the Norwegian Channel. The Channel was formed by large-scale ice flow erosion after major climatic deteriorations at around 1.1 Ma.

- The North Sea Fan megasequence was formed by deposition of detritus transported by ice streams through the Norwegian Channel. The North Sea Fan megasequence and its sequences SS19-31 corresponds to megasequence II of the Norwegian Channel. SS19 to 20 were likely deposited within the time interval 0.8 to 0.6 Ma, while there probably was a hiatus in the channel. SS21-31 were formed since about 0.6 Ma, when ice streams repeatedly flowed through the Norwegian Channel.

- The North Sea Fan is dominated by debris flow deposits and slides with intercalations of hemipelagic mud. Two major slides, the Møre and Tampen slides and the seismic sequences in between, probably correspond to the sequence SS-C in the Norwegian Channel and represent the major glaciations Elasterian and Saalian, respectively. Seismic sequences SS-28 to SS-31 are interpreted to correlate with sequence SS-D in the channel, formed during the Weichselian, possibly representing stadial/interstadial cycles.

- The formation of the glacigenic sequences and their depositional style was controlled by basin morphology, accommodation space as function of basin depth, glacioeustatic changes and differential compaction, besides variation in rate of sediment supply through glacial ice sheets and changes in direction of glacial transport direction.

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